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## DEVELOPING AN EMISSION FACTOR FOR HAZARDOUS AIR POLLUTANTS FOR AN F-16 USING JP-8 FUEL

THESIS

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THESIS

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Table of Contents

List of Figures

List of Tables

Abstract

The 1990 Clean Air Act Amendments drastically changed the legislation of hazardous air pollutants or air toxics. Title III of the act which specifically addresses HAPs now lists 189 substances (instead of the previous 7) which may require regulation as air toxics. Consequently, the reporting of HAP emissions from all Air Force operations will be required in the future. Currently, some states are already requiring the reporting of this information. However, the Department of Defense (DoD) does not have any methods available to report this information.

This thesis develops emission factors for selected HAPs from an F-16 C&D aircraft/F110 engine operating on JP-8 fuel. JP-8 was chosen because the Air Force is in the process of converting from JP-4 to JP-8. The methodology included: (1) determining which HAPs should be selected, (2) using past aircraft emission studies to develop estimated HAP concentrations for the F110 engine using JP-8 fuel, (3) determining an emission factor formula to use to calculate emission factors for each HAP, (4) testing the developed emission factor for each of the selected HAPs on an airfield operation.

The estimated emission factors are very small for all HAPs at all engine operating conditions of the F-16 C&D aircraft mainly because the F110 is a new engine and has a high combustion efficiency. Emission factors may vary depending on the type of engine. The resultant emission inventory for an airfield operation shows that the only potential area of concern is when the engine operates at afterburner. The HAP emission inventory can be used to compare against HAP legislation to determine if an air quality problem exists at the base.

DEVELOPING AN EMISSION FACTOR FOR HAZARDOUS AIR POLLUTANTS FOR AN F-16 USING JP-8 FUEL

1. Introduction

Problem Background

The 15 Nov 1990 signing of the 1990 Clean Air Act (CAA) amendments drastically changed the legislation of hazardous air pollutants (HAPs) or air toxics. Title III of the act specifically addresses HAPs. Title III lists 189 substances which are presumed to require regulation as air toxics. The Environmental Protection Agency (EPA) may add or delete substances from the list. EPA is commanded to impose tight controls in accordance with a new two-phase strategy (Quarles et al., 1990:31). The first phase establishes technology standards and will require industries to install Maximum Achievable Control Technology (MACT). The second phase addresses the residual risk from facilities which may still create concentrations of air toxics even after the implementation of MACT. EPA must determine if these facilities require further regulation.

Not only did the 1990 CAA amendments list 189 HAPs, they also required EPA to identify all sources of these pollutants within a year of enactment (Congress,1990:2532). The amendments define two types of sources. A major source is any stationary source that has the potential to emit 10 tons per year of any single HAP or 25 tons per year of a combination of HAPs. Area sources are sources which when viewed individually do not have a significant impact on air quality but may when viewed collectively (Godish, 1991:27). Examples of area sources are motor vehicles, aircraft, and open burning. EPA was also required to establish emission standards for all listed industries on a schedule that will result in the regulation of all listed source categories within ten years of enactment.

One source of HAP emissions common to Air Force installation is jet engines. In the past, the reporting of jet engine emissions was not required by the military. However, with the passage of the Federal Facilities Compliance Act of 1992, the federal government is no longer exempt. Part of this legislation required that the EPA:
undertake a thorough inspection annually of each facility owned or operated by a department, agency, or instrumentality of the United States that is subject to Resource Conservation and Recovery Act (RCRA), Clean Water Act (CWA), Clean Air Act (CAA), Toxic Substances Control Act (TSCA), and Safe Drinking Water Act (SDWA) (RCO, 1992:6).
Consequently, EPA will be able to determine if the military is complying with requirements of each of these acts.

Besides Title III, there are two additional titles of the 1990 CAA amendments which must be reviewed when assessing the impact of jet engine emissions.

Title I is entitled "Provisions for Attainment and Maintenance of National Ambient Air Quality Standards (NAAQS)." This title places restrictions on those sources which contribute to the urban air pollution problems of ozone (smog), carbon monoxide (CO) and particulate matter (Hauser, Summer 1993). Aircraft are one source of these pollutants.

Title II which is entitled "Provisions Relating to Mobile Sources" also applies to aircraft. This title establishes tighter pollution standards for emissions from mobile sources. Although Titles I, II and III of the 1990 CAA amendments are all applicable to aircraft emissions, this thesis will focus only on Title III.

DoD Applicability

Currently, the Department of Defense (DOD) is concerned with quantifying the HAPs which are present in jet engine exhaust. Within the last year, state regulators in North Carolina directed two Air Force bases (Pope AFB and Seymour-Johnson AFB) to provide

2

emission inventories for those necessary sources which emit HAPs (Isaacs, 24 Feb 94). One such source is a jet engine while it is operating in a test cell or idling on the ground. A test cell is a facility used to test jet aircraft engines. Thus, while in these modes, the emissions of toxic compounds must be reported (AESO: 1991:1). Aircraft which are taxing down a runway or which are airborne are classified as mobile sources and are not yet subject to HAP emission reporting. However, once the EPA establishes the MACT standards, HAP emission reporting will be required. Meanwhile, some state regulations are more stringent, and the regulators are now requiring HAP emissions reporting. The two bases listed above fall under Air Combat Command (ACC) and they are interested in compiling HAP emission inventories for its aircraft.

The environmental personnel at the bases were unable to provide the regulators with the necessary information because no procedures exist within the DoD to report HAP emissions from jet engines. In order to accurately estimate these emissions, it is necessary to develop an emission factor for each HAP in the jet engine exhaust to meet the requirements of Title III of the CAA. Once an emission factor is calculated, an emission inventory can be developed and provided to regulators.

Goal of Research

The goal of this research is to develop an emission factor for selected hazardous air pollutants (HAPs) or air toxics found in the exhaust of an F-16 aircraft operating on JP-8 fuel. The F-16 currently operates on JP-4 fuel, but the Department of Defense (DoD) is in the process of converting to JP-8 fuel. The completion date for full conversion is fiscal year 1996. An emission factor will allow HAP emission inventories to be compiled for the F-16 aircraft.

Research Objectives

The following research activities will be conducted to meet the goal:

1) Determine which HAPs are present in the highest concentration in jet engine exhaust.

2) Use past aircraft emission studies to develop a model for the HAPs found in the exhaust of an F-16 using JP-8 fuel.

3) Review emission factor formulas and calculate an emission factor for each of the HAPs identified at each power setting of the F-16.

4) Test the emission factor by compiling an emission inventory on an airfield operation.

Scope/ Limitations of Research

Scope. The scope of this research is to develop emission factors for selected HAPs which have been found to be predominant in jet engine exhaust based on previous engine studies. The study will only focus on the F-16 aircraft using JP-8 fuel. This study will attempt to use data from previous aircraft emission studies to estimate HAP emissions from an F-16 using JP-8 fuel. The previous studies used the same/different engines operating on either JP-4, JP-5, or JP-8. However, none of the previous works presented data exclusively for the F-16 engine with JP-8 fuel. Differing engine type and fuel type will result in different concentrations of HAPs found in the exhaust. Consequently, the emission factors will also be different.

Limitations. The emission factor for each HAP will be calculated by using concentrations of HAPs which will be estimated from previous studies instead of actual measurement of emissions. However, the emission factors proposed in this study should be considered the best available emission factors available for HAPs emanating from jet aircraft. These emission factors will allow emission inventories to be compiled.

Additionally, only two studies have measured the individual organic compounds or substances comprising the jet engine exhaust. The availability of more data from jet engine emission testing would provide a better estimate of emissions for the F-16 aircraft using JP-8 fuel.

2. Literature Review

Legislation of Aircraft Emissions

The visibility of smoke exhaust from an aircraft first brought about public concerns of the health effects from these emissions. Jet engine emissions which have received attention in recent years are hydrocarbons, carbon monoxide (CO), particulates, nitrogen oxides (NO_x), and sulfur oxides (SO_x) (Nelson et al., 1992:1). NO_x is considered a precursor to smog and acid rain. CO is a highly toxic gas and particulates can darken a normally clear sky (Nelson et al., 1992: 1). It can also cause health effects depending on composition. Hydrocarbons in a jet exhaust are the result of incomplete combustion of fuels, particularly volatile ones. Hydrocarbons become a health hazard because of their reaction with other pollutants and sunlight, producing photochemical smog (Fagin, 1988:2). In a study conducted by Johnson et al., model results and measurements showed that growth in the aircraft surface emissions of nitrogen oxides and hydrocarbons lead to increases in trophospheric ozone. Trophospheric ozone is a greenhouse gas and is toxic to plants, humans and other organisms (1992:69).

The first legislation which attempted to research the impact of aircraft emissions was the Air Quality Act of 1967. This act directed the Secretary of Health, Education and Welfare to conduct:

> a full and complete investigation and study of the feasibility and practicability of controlling emissions from jet and piston aircraft engines and of establishing national emission standards with respect thereto (Springer and Patterson, 1973:267).

The Air Quality Act of 1967, along with increasing public awareness of aircraft as a visible source of pollution, led to the conclusions that a real and immediate need existed for a set of uniform standard procedures to be used to measure emissions from aircraft gas turbine engines (Elwood and Dieck, 1975:839). As a result, the Society of Automotive Engineers

(SAE) E-31 committee was formed in 1968 to develop standard methods for the measurement of exhaust emissions from aircraft engines.

The Clean Air Act (CAA) of 1970 also addressed aircraft emissions. Part B to Title I of the act sets emission standards for aircraft. In this part, the Environmental Protection Agency (EPA) administrator is directed to issue emission standards within 180 days for those aircraft he feels may contribute to air pollution and can reasonably ᵇ   icipated to endanger public health or welfare (Naugle and Fox, 1981:3911). It also t   ᵔPA to research the technological feasibility of controlling emissions and also determine the extent to which emissions will affect air quality control regions (AQCRs) in the United States (US. Congress, 1970:1988). AQCRs were designated in the 1970 CAA because iᵗ was recognized that air pollution was a regional problem and did not respect political boundaries (Godish, 1991:252). Thus, Congress mandated that both interstate and intrastate AQCRs be established. One of the required standards promulgated by the EPA in 1973 was entitled "Control of Air Pollution from Aircraft and Aircraft Engines." It set emission standards for total hydrocarbons, carbon monoxide, nitrogen oxide and smoke. The testing procedures for the aircraft were also indicated (Naugle, 1973:9).

Although the 1990 CAA amendments did not specifically address aircraft, it did recognize that mobile sources generate the largest single share of national inventory of precursor pollutants (US. Congress, 1990:3469) that react in sunlight with other pollutants to form ozone. Ozone is a health concern because it affects the respiratory system when present in sufficient concentrations. Consequently, the 1990 CAA amendments substantially tightened the mobile source emission standards and currently require a 50% reduction in mobile source emissions beginning in the year 2003 (Arbuckle et al., 1993:139). The biggest impact of the 1990 CAA amendments was in the area of HAPs.

Legislation of HAPs

Although HAPs were first regulated in the 1970 CAA, only 7 HAPs were addressed. This number remained the same for 20 years. The reason for the slow pace in dealing with air toxics was because the CAA required setting emissions standards based on margin of safety. Since many air toxics are carcinogenic, EPA interpreted this to mean that an emission standard of zero was required (Godish, 1991:258). Thus, EPA delayed regulation of HAPs for a fear of a total ban of substances would be economically disastrous. The zero emission standard came about from congressional action entitled the Delaney Clause, which stated that no food product may contain any concentration of carcinogenic material (Shelley, Fall 1993). EPA attempted to confront the zero risk problem head-on and set standards requiring the tightest level of controls which were found to be technologically and economically feasible. However, the 1987 vinyl chloride decision changed EPA's approach. In this case, the Court of Appeals stated that EPA's standards were unconstitutional and thus brought the program to a total halt (Quarles et al., 1990:33).

The 1990 CAA amendments drastically changed the legislation for hazardous air pollutants which was brought about, in part, by the information obtained from the Toxic Release Inventory (TRI) (Vercera, 1993:40). The TRI was ordered by the Superfund amendments of 1984 and was a survey of all toxic releases. The results found that a total of 2.7 billion pounds of air emissions was reported for the year 1987 (Vercera, 1993:41). This data brought about great concerns about HAPs and agreement that revisions in their regulation was needed. As a result of the survey, the focus of regulation shifted from a risk-based approach to a technology approach. Health advocates recognized that the existing approach was producing no results, while industry leaders accepted that controls of technology would provide public assurance that maximum efforts were being taken to reduce health risks (Quarles et al., 1990:33).

The 1990 CAA amendments also overhauled the air toxics program. The new program was an attempt to correct some of the perceived problems that led to the air toxic programs' poor record (Mohin, 1992:13). Under Title III of the 1990 CAA amendments, 189 HAPs are now regulated instead of the previous 7. These HAPs were selected because they were linked to birth defects, adverse reproductive effects, neurological disorders, and genetic damage (Manz, 1991:3). By listing 189 HAPs to be regulated, Congress answered one of the major complaints concerning EPA's lack of responsiveness under the old section 112 and forced the agency to act (Vercera, 1993:44).

The revisions to the air toxics program under the 1990 CAA amendments demonstrate that Congress is concerned with controlling HAPs emissions. The DoD, as well as industry, will have to assess their operations for emission of HAPs and ensure compliance under Title III of the 1990 CAA amendments. Currently, reporting of HAP emissions will not be required until EPA establishes the standards. However, some state regulations are more stringent than federal standards, and they are requiring HAP emission reporting. To accurately estimate HAP emissions from jet aircraft, an emission factor (or an acceptable surrogate) must be developed for each HAP.

Emission Factor

The purpose of emission factors is to estimate the collective emissions of a number of sources for designated pollutants for a selected area. Emission factors are widely used because they substitute for measuring the actual emissions of each source (Pope, 1990:7). An emission factor is defined as "the estimate of the rate at which a pollutant is released to the atmosphere as a result of some activity (such as combustion) divided by the level of that activity" (Fagin, 1988:99). For example, an emission factor for the combustion exhaust of an aircraft turbine engine is the ratio of the amount of the pollutant to the amount of fuel used per engine operating mode(eg., idle, approach,etc.). Because aircraft engines use large amounts of fuel, it is convenient to express the emission factor as units

8

of mass per hour divided by 1000 units of mass per hour (AESO, 1991:2). For example, the emission factor can be expressed as pounds of the pollutant per 1000 pounds of fuel or any other mass units such as grams of pollutant per 1000 grams (kilogram) of fuel.

It is important to note that the emission factor for an aircraft is not a constant value. It will vary for the different operating sequences of the engine: idle, approach, intermediate, military and afterburner (for fighter aircraft). It has been shown that hydrocarbons emitted by gas turbine engines are significantly higher in the idle and takeoff modes than in taxi, cruise and approach modes of operation (Springer and Patterson, 1973:121-2). Percentage equivalents of these sequences are also used. For example, approach sequence is the same as 30% power. Additionally, emission factors for the same power setting can vary not only among engines of the same type and model but among the same power setting if used for different operating times (AESO, 1987:1-1). To accurately calculate an emission factor for any pollutant in the exhaust of a gas turbine engine, present techniques discovered that measurements of the concentration of that pollutant along with the concentrations of carbon monoxide, carbon dioxide, and total hydrocarbons are needed (AESO, 1991:2).

The calculation of an emission factor can be done by one of two formulas shown in Table 1. Equation (1) can be found in a document entitled "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines" (AESO, 1987:4-1). This document is also referred to as Aerospace Recommended Practice (ARP) 1256A which was written by the SAE as one of the standards directed under the 1970 CAA. Equation (1) is the best method to make a quick estimation of emission factors. Note that in equation (1), T is subtracted in the denominator. This is necessary because the ambient (outside) air contains carbon dioxide; thus, this concentration must be subtracted from the concentration of carbon dioxide found in the exhaust to get a more accurate carbon dioxide concentration.

Table 1-1

Emission Factor Formulas

$$EI(Z) = \left[\frac{[Z]}{[CO] + [CO_2] + [C_x H_y] - T} \right] \left[\frac{M_z \times 10^3}{M_c + \alpha M_H} \right] \qquad (1)$$

$$EI(Z) = \left[\frac{[Z]}{[CO] + [CO_2] + [C_x H_y]} \right] \left[\frac{M_z \times 10^3}{M_c + \alpha M_H} \right] [1 + TX/M] \qquad (2)$$

Where:

- $EI(Z)$ is the emission index of Z (HAP) as pounds of Z produced per 1000 pounds of fuel used.

- $[Z]$ is the mole fraction concentration of a constituent Z (HAP) of the exhaust, specifically the mole fraction concentration of carbon monoxide, carbon dioxide, oxides of nitrogen, or hydrocarbon or HAP.

- M_Z is the molecular weight of the constituent, specifically: carbon monoxide (28.01); carbon dioxide (44.0098); nitrogen dioxide (46.0055); or hydrocarbons (usually represented as methane (16.043)).

- M_C is the atomic weight of carbon (12.011).

- M_H is the atomic weight of hydrogen (1.008).

- α is the hydrogen-carbon ratio of the fuel

- T is the mole fraction of carbon dioxide in the dry inlet air (0.00032).

- X is the number of moles of dry air per mole of fuel in the initial air fuel mixture.

- M is the molecular constant for carbon in the fuel $C_m H_n$.

(AESO 1991:3)

10

The equation in the first set of brackets represents the number of moles of each respective HAP divided by the moles of fuel. The equation in the second bracket represents the molecular weight of each respective HAP divided by the molecular weight of the fuel (SAE, 1980:L-21).

Equation (2) is a product of another SAE document (SAE AIR 1533). SAE recommends this publication as the national standard for calculation of emission factors (AESO, 1987:2-2). Equation (2) should be used when more specific data is available on the exhaust of the aircraft and thus, the variables for the equation are defined. Because of the limited data on the engine testing for HAPs, this study will use equation (1) to develop an emission factor for each HAP. Developing an emission factor is extremely important in developing an accurate emission inventory.

Emission Inventories

Emission inventories are of importance to regulators because they can point out the locations of major sources of pollution. Thus, based on this information, the regulators can take steps to reduce these emissions. Simply put, an emission inventory is a list of the amount of pollutants entering the air in a given time period in a given area (Hauser, Summer 1993).

To calculate an emission inventory for aircraft emissions, the following formula is used: (Seitchek, 1985:7)

$$W = N \bullet F \bullet t \bullet e$$

where W = Total aircraft emissions (in grams)

    F = Fuel flow (kg/s)

    N = Number of engines

    t = time in engine mode (seconds)

    e = emission factor for the pollutant (g/kg or lb/1000 lbs)

Thus, to use this equation to calculate the emissions for a specific pollutant, the user needs to know the correct fuel flow, the emission factor for that pollutant, the number of engines and the time in engine mode. To find time in mode, the length of time spent in each operating mode of the aircraft must be known. Once emissions for each mode are calculated, they are summed to give the emission inventory for that aircraft.

Jet Engine Emission Testing

Because of the 1973 standards for testing of aircraft emissions, DoD started performing engine emission studies. The DoD conducted a three year emission survey from 1975 to 1977 to analyze air pollution from jet engine emissions (Souza and Daley, 1978). This survey sampled the most common Air Force engines and measured concentrations in the exhaust for hydrocarbons, carbon monoxide, nitrogen oxide, and particulate emissions. Using the results of the survey, emission factors were developed for these engines (Scott and Naugle, 1978). These emission factors were later updated and then used to calculate aircraft emissions from landing-and-takeoff (LTO) and touch-and-go (TGO) operations (Seitchek, 1985). Unfortunately, when these emission factor catalogs were compiled, regulators were mainly interested in smoke exhaust and documentation of gaseous emissions. Thus, the emission factors did not attempt to quantify the individual organic compounds which make up the exhaust. Accurate speciation of the compounds in the exhaust is necessary in order to identify HAPs and develop an emission factor for each one. Currently, there is a combined Air Force and Navy program to review data on all available military gas turbine engines, assess the validity of the data, and develop an updated emission data base (Spicer et al. 1990:1).

In the past, there have been several studies which attempted to quantify the individual organics in the exhaust of an aircraft. The first of these studies took place in 1975. This study measured the hydrocarbon constituents of a T-56 engine as a function of fuel type and combustor operating pressure (Conkle, 1975). This study used JP-4, JP-5 and JP-8

12

fuels and compared the effect of each fuel on emissions. The study found that the exhaust concentrations of hydrocarbons were higher for JP-5 and JP-8 fuel than for JP-4 fuel. Since JP-5 and JP-8 have higher boiling points and densities than JP-4, Conkle stated that there is a relationship between boiling point/density and exhaust emissions (1975:6). Unfortunately, this study only used one engine type with different fuels.

A later study, which also identified the organic compounds within the exhaust, tested two common Air Force engines, the TF-39 and CFM-56 (Spicer et al., 1984). This study was conducted by Battelle Laboratories. The engines were tested at different power settings using three different fuels (JP-4, JP-5 and JP-8 (shale-derived)). This study again showed the differences in exhaust emissions based on differing fuel type. However, this study was important because it also compared the effects on exhaust emissions of two different engines operating on the same fuel type. The results showed that engine type is also a factor in concentrations of exhaust emissions. Also, it enabled a comparison can be made based on changing fuel type or engine model.

The above two studies looked at the gaseous emissions of aircraft. However, the particulate emissions are also important. Particulate matter is one of the six national primary and secondary Ambient Air Quality Standards. These standards define sufficient levels of air quality to protect public health and welfare. In other words, the EPA has set maximum levels of particulate which can be emitted into the air. Exhaust particles are responsible for much of the visible emissions from jet engines and consist of a complex collection of aerosols that varies qualitatively and quantitatively as a function of engine type, fuel composition and operating mode (Kuhlman and Chuang, 1989B:1). A large portion of the particles are composed of unburned carbon, which is black, relatively stable, and not a significant health threat (Kuhlman and Chuang, 1989A:1). Particulate bound organics form a small fraction of the total organic composition of the jet exhaust from a mass balance standpoint. However, these chemicals may be occupationally and environmentally significant because of the small size of the typical exhaust particles

13

(Kuhlman and Chuang, 1989:1-2). Because of the importance of sorbed particulate emissions, a study was conducted by Pratt and Whitney to research solid particulate matter (mainly carbon) when emitted in the exhaust of an aircraft. The study specifically assessed the organic species which absorbed onto the particulates. The study found that although the organic material found on the particulates was less than 1%, it was still important because of the potential to be respired (Robertson et al., 1980).

The DoD also conducted a study to measure the particulate emissions from selected aircraft engines (AESO, 1990A) and this study was incorporated with previous gaseous emission studies to list tables showing the gaseous and particulate emissions for numerous DoD engines (AESO, 1990B). This study also provided emission factors for the engines. These emission factors can allow the user to calculate emission inventories simply by supplying the times of operation from each operating cycle of the engine. However, these emission factors, like the previous ones proposed, were for hydrocarbons and particulates as a whole and did not attempt to quantify the individual compounds found in the exhaust.

The only study which has attempted to propose emission factors for HAPs was conducted by the Navy. This study used the results of the 1984 Battelle study which was previously discussed. Since the Battelle study was conducted before the listing of the 189 HAPs (1990 CAA), it simply listed all the compounds or substances present in the exhaust in measurable concentrations. The Navy study separated the HAPs from the listing and proposed emission factors for each HAP at each engine operating mode. Since the Navy uses JP-5 fuel, emission factors were proposed only for that fuel. The study assumed (because of lack of data) that the same HAPs will be found in the exhaust of all engines at the same level for all power settings. The Navy concluded that HAP emissions will not change significantly from engine type, but that fuel differences can result in significant differences in emissions.

An important study by Spicer and others quantified the organics in the exhaust of F101 and F110 engines (Spicer et al., 1990). This study is of significance because the F110

14

engine is used in the newer model F-16s (F-16C and F-16D), and this aircraft is the model for this thesis. Both engines were tested using JP-4 fuel. The study reported comprehensive measurements of inorganic and organic gaseous and particulate emissions. This study found that the predominant organic chemical in the exhaust was methane. Additionally, four compounds (ethane, acetylene, propene, and formaldehyde) accounted for 20-30% of the emissions at idle power. These results will be further analyzed later in this thesis.

In summary, although there have been studies to assess the emissions from aircraft, only a few studies have looked at the organic compounds which make up the exhaust emissions of an aircraft. These studies are important because by knowing the actual compounds in the exhaust, the number of HAPs can also be identified. Only one study (AESO, 1991) proposed emission factors, but those were for Navy engines using JP-5 fuel. The Air Force has no proposed emission factors for their engines operating on JP-4 fuel. More importantly, less data is available on JP-8 fuel which the Air Force will completely convert to by fiscal year 1996. With recent increasing legislation of HAPs, the Air Force will soon be forced to comply with reporting of HAPs for all their operations, a large part of which are aircraft operations. To accurately report HAP emissions from aircraft, it is necessary to develop an emission factor for all operating conditions of the aircraft using JP-8 fuel.

3. Methodology

Introduction

As mentioned in the previous chapter, only two studies were conducted which quantified the exhaust of a jet engine and identified the individual compounds; the Spicer et al. study of 1984 on the CFM-56 and TF-39 engines and the Spicer et al. study of 1990 on the F101 and F110 engines. Thus, these are the only studies which can be used to estimate HAP concentrations for the F110 engine using JP-8 fuel. Figure 3-1 shows the availability of engine testing data for each of these engines for each fuel and each engine operating condition. It is important to note that the F-16 C and D models uses the F110 engine which is one of the engines listed in Figure 3-1. However, existing data is only for JP-4 fuel. One of the objectives of this thesis is to estimate the emissions from this engine for JP-8 fuel.

The method which will be used to estimate HAP emissions from the F-16 aircraft/F110 engine using JP-8 fuel will use the existing data from the two studies shown in Figure 3-1. From analyzing Figure 3-1, it can be seen that there is HAP emission data which is missing. For example, both the CFM-56 and TF-39 engines have been tested on all operating cycles of the engine for JP-5 fuel; however, JP-4 and JP-8 fuel have only been tested at idle. Likewise, the F110 and F101 engines have HAP emission data for all cycles of the engine but for JP-4 fuel only. Thus, the only way to estimate an emission factor for the F110 engine using JP-8 fuel will be to look at the effect of differing fuel type and differing engine type on exhaust emissions and then an emission factor may logically be proposed. Two methods will be used to accomplish this and they are discussed in detail later in this chapter. Also, note that the F110 and F101 engines have engine operating modes called Intermediate and Afterburner. The intermediate setting is also referred to as 105% Mach power while afterburner is referred to as Stage I augmentation.

Figure 3-1

HAP Emission Data From Previous Studies

B-1B Aircraft
— F101 Engine
- JP-4: Idle, 44%, 75%, Intermediate, Afterburner
- JP-8: ?, ?, ?, ?, ?

F-16 C&D Aircraft
— F110 Engine
- JP-4: Idle, 30%, 63%, Intermediate, Afterburner
- JP-8: ?, ?, ?, ?, ?

KC-135 Aircraft
— CFM-56 Engine
- JP-4: Idle, ?, ?
- JP-5: Idle, 30%, 80%
- JP-8: Idle, ?, ?

C-5 A,B Aircraft
— TF-39 Engine
- JP-4: Idle, ?, ?
- JP-5: Idle, 30%, 80%
- JP-8: Idle, ?, ?

17
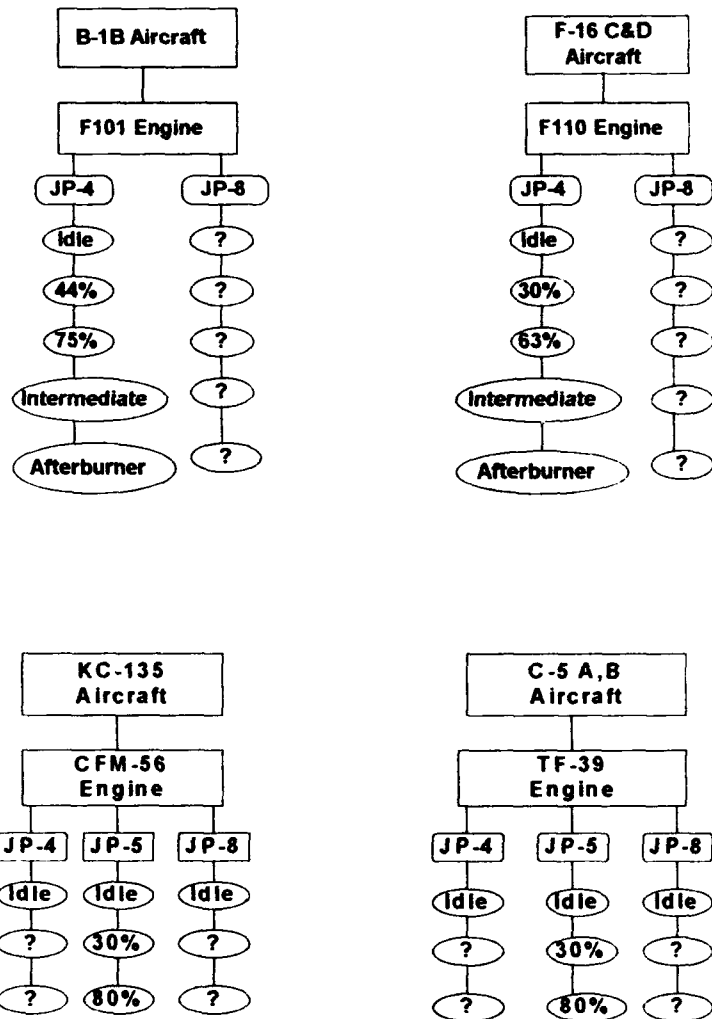
By using the two studies discussed above, concentration of HAPs from the F-16 C&D aircraft/F110 engine using JP-8 fuel can be proposed. However, in order to calculate the emission factors for HAPs, mole fraction concentrations of carbon monoxide, hydrocarbons and carbon dioxide will also be required. Thus, past emission studies will also be used to estimate these emissions in an F-16 operating with JP-8 fuel.

There have been many more studies for measuring CO, C_xH_y, and CO_2 than for individual HAPs. These studies all measured the concentrations of CO, C_xH_y, and CO_2 for the engines using JP-4 and JP-5 fuels. Additionally, the studies by Spicer et al. which measured the individual species of the exhaust also measured CO, C_xH_y and CO_2 for the JP-4, JP-5 and JP-8 (Spicer, 1984). Consequently, comparisons of all these studies can be made in order to propose CO, $CxHy$ and CO_2 concentrations for the F110 engine using JP-8 fuel.

To logically come up with the concentrations of HAPs, carbon monoxide, hydrocarbons and carbon dioxide and eventually an emission factor for each HAP at each engine operating mode, the following procedure is required:

1) Select the HAPs from the list of 189 in the 1990 CAA for which emission factors will be proposed.

2) Assure that data from the previous studies can be converted to the necessary format for use in the emission factor calculation.

3) Explain how engine type and fuel type differences from past studies play a part in emission concentrations and how they may be used to estimate HAP emissions for JP-8 fuel in an F-16 aircraft.

Selection of HAPs

The following HAPs are selected and an emission factor will be developed for each HAP at each different operating condition of the engine.

1) Toluene   6) m + p-Xylene

2) Formaldehyde   7) o-Xylene

3) Acetaldehyde   8) Acrolein

4) Benzene   9) Ethylbenzene

5) 1,3-Butadiene

Two criteria were used to determine the selection of HAPs. The first criteria was the

concentration of these HAPs found in the exhaust from previous engine emission tests.

The two Spicer studies previously mentioned quantified the constituents of the exhaust.

The concentrations of the nine HAPs are found in Table 3-1. The table shows

concentrations of the idle mode only since the maximum concentration level of the HAPs

is found at this engine operating mode. Additionally, the concentrations are listed for JP-4

fuel only for comparison purposes. The second criteria used to select the HAPs for this

study was the health effects involved with exposure to the compound. A description of

Table 3-1

HAP Concentrations in Exhaust of Three Aircraft at Idle (JP-4 Fuel)

HAP	F-16 C&D Aircraft/ F110 Engine (ppmC)**	C-5 A&B Aircraft/ TF39 Engine (ppmC)	KC-135 Aircraft/ CFM56 Engine (ppmC)
Toluene	.985	5.19	1.26
Formaldehyde	.305	14.7	9.3
Acetaldehyde	.14	8.2	2.1
m + p-Xylenes	.086	5.46	1.25
Benzene	.079	7.7	1.95
Ethylbenzene	.024	1.78	.45
1,3 Butadiene	.034*	7.7	2.1
o-Xylenes	.03	2.4	.54
Acrolein	.015	6.2	2.4

(Spicer et al., 1984: 39-41 and Spicer et al., 1990:28)

* Indicates combination of 1,3 Butadiene and 1-Butene

** ppmC = mole fraction of hydrocarbons multiplied by 10^6 on a (C_1H_n) equivalence basis

the health effect of each HAP follows.

Health Effects

   Toluene. Toluene is produced primarily from petroleum or petrochemical processes. It is an aromatic hydrocarbon which is both volatile and flammable. The main hazard associated with acute exposure to high levels of toluene is excessive central nervous system depression (EPA, 1990: C-15). Additionally, inhalation of relatively low concentrations of toluene may be irritating to mucus membranes and can produce psycho physiological functions.

   Formamaldehyde. Formaldehyde is both a primary anthropogenic (from combustion sources) pollutant and a secondary pollutant which forms during the photochemical oxidation of hydrocarbons in the troposphere (Nriagu, 1992:31). Formaldehyde is a suspected animal carcinogen and a potential occupational carcinogen. The route of entry into the body is through inhalation and skin absorption. Gaseous formaldehyde causes severe irritation of mucous membranes in the respiratory tract and eyes; high concentrations can cause breathing difficulty and pulmonary edema (Spicer et al., 1984:56-7).

   Acetaldehyde. Acetaldehyde is an aliphatic aldehyde which is highly reactive and readily oxidizes in air (EPA, 1987:1-1). Humans are frequently exposed to acetaldehyde from cigarette smoke or exhaust fumes. The primary acute effect of exposure to acetaldehyde is irritation of the eyes, skin and respiratory tract, and at high concentrations irritation effects can occur which could facilitate the uptake of other contaminants (EPA, 1987:1-4).

   Xylenes (m,o + p). Xylene usually results from fuel combustion or biomass burning (Nriagu 1992:225). Based on case reports of occupationally exposed individuals, a short term exposure to xylene may cause central nervous system depression and minor irreversible effects on the liver and kidneys; at high concentrations, exposure to xylene can

lead to dizziness, staggering and unconsciousness (Calabrese and Kenyon 1991:575).
However, data which correlates exposure levels with these effects is lacking.

Benzene. Benzene is an environmentally significant compound because it has shown
to cause leukemia in workers exposed to high concentration levels (Spicer et al., 1990:55).
Benzene usually enters the body through inhalation of the gas. Acute exposure to benzene
can cause nausea, dizziness, headaches and convulsions. Chronic exposure affects the
blood and could lead to anemia and other blood diseases.

Ethylbenzene. Ethylbenzene is used primarily as a solvent. It is considered volatile
and only slightly soluble in water and is an infrequent and very low level contaminant in
drinking water, based on national surveys (Calabrese and Kenyon, 1991:313). Data is
lacking on the effects from chronic inhalation of ethylbenzene. However, the target
organs for acute high-level exposure (5000 to 10,000 ppm) are the lungs and central
nervous system, but longer, lower level exposure results in effects on the visceral organs
(Calabrese and Kenyon, 1991:312).

1,3-Butadiene. 1,3-Butadiene is a gas at room temperature and pressure but is soluble
in water and has been detected in drinking water. It has been found to show
carcinogenicity in rats and mice. There have also been effects on the reproductive system
(Calabrese and Kenyon, 1991:178).

Acrolein. Acrolein is a flammable, unstable liquid and has a wide variety of
applications. Acrolein is often found in small amounts in food and is a component of
smog, fuel combustion, and cigarette smoke (EPA, 1980:C-1). Acute inhalation of
acrolein has been shown to affect the lungs. Chronic toxicity has shown eye irritation and
nasal discharges.

Because of the health effects of the HAPs and their concentrations in the exhaust of
two studies listed above, these nine HAPs were determined to be the critical ones for
which to develop an emission factor.

Emission Factor

The next objective is to arrange the necessary data so it can be used in the emission factor formula. The two equations for emission factors were given in Chapter 2. Both the AESO and SAE Technical Board recommends both formulas for the calculation of emission factors from gas turbine engines. The EPA and International Civil Aviation Organization (ICAO) also propose emission factors for aircraft. Their formulas are presented in a different format but still require calculation of the same variables. The first equation shown in Table 1-1 was:

$$EI(Z) = \left[\frac{[Z]}{[CO] + [CO_2] + [C_xH_y] - T} \right] \left[\frac{M_z \times 10^3}{M_C + \alpha M_H} \right]$$

and this equation was used for this study because the data available from past studies allows the calculation of all the necessary variables in the equation.

To calculate an emission factor for each HAP for an F-16 with JP-8 fuel, the most important variables in the calculation are the concentrations of each HAP ($[Z]$), carbon dioxide ($[CO_2]$), carbon monoxide ($[CO]$), and hydrocarbons ($[C_xH_y]$). It will be necessary to measure these concentrations at each power setting of the engine; thus, each HAP will have a different emission factor for each power setting. The symbol [ ] around CO_2, CO, C_xH_y, and each HAP represents the mole fraction concentration of each substance. A mole fraction is defined as the number of moles of that substance divided by the total number of moles in the system; for a mixture of ideal gases, the mole fraction is equal to the volume fraction which is found by dividing the volume of the component at the total pressure and temperature by the volume of the entire mixture at the same pressure and temperature (Cassidine, 1984:594).

Data from jet engine emission testing usually represents CO in parts per million (ppm), C_xH_y and each HAP in parts per million carbon (ppmC) and CO_2 in percent. Thus, it is

22

necessary to convert the concentration of each substance into its respective mole fraction concentration. To convert a quantity expressed in ppm to a mole fraction concentration, divide the amount expressed in ppm by 10^6 (AESO, 1987:3-1). For example, if a concentration of 40 ppm of CO was measured in the exhaust of a jet engine then the conversion to a mole fraction concentration would be:

$$40 \text{ ppm} = 40/10^6 = 40 \times 10^{-6} = [4 \times 10^{-5}].$$

To convert ppmC to a mole fraction concentration, first convert ppmC to ppm and then to a mole fraction concentration using the procedure described above. A ppmC is defined as the mole fraction of hydrocarbon multiplied by 10^6 measured on a (C_1H_n) equivalence basis (SAE 1980, L-3). To convert ppmC to ppm divide the ppmC by the number of carbon atoms per molecule of the gas. For example, benzene has a carbon number of 6. A concentration of benzene of 6 ppmC would be equivalent to 1 ppm. Finally, CO_2 is normally given in percent. To convert percent to a mole fraction concentration, divide by 100. For example:

$$40\% = 40/100 = 40 \times 10^{-2} = [4 \times 10^{-1}].$$

The mole fraction concentration of hydrocarbons (C_xH_y), as previously mentioned, is usually reported in ppmC. However, there are many constituents which make up the hydrocarbons in the exhaust of a jet engine. Therefore, in order to convert ppmC to ppm for hydrocarbons, convention is to treat the hydrocarbons in the exhaust as if they are made up of methane (Spicer, 28 Jan 1994). Since methane has a carbon number of 1, then ppmC = ppm. The rationale behind this is that using methane represents the worst case; since its carbon number is one, the resulting ppm value will be a maximum value. This convention will be used for the calculation of the mole fraction concentration for hydrocarbons.

The final variable to find is α which represents the hydrogen-carbon ratio of the fuel. This variable is typically found by determining the molecular contents of the fuel (C_xH_y) where the ratio y/x is the hydrogen-carbon ratio of the fuel (AESO, 1987:3-5). When these variables have not been determined, the AESO recommends using 2 for JP-4 fuel ($y=19$ and $x=9.5$) and 1.8 for JP-5 fuel ($y=23.4$ and $x=13$). Since the makeup of JP-8 fuel is very similar to JP-5 fuel, this study will assume a factor of 1.8 also for α.

Methodology

Now that all the variables have been identified and methods to calculate them have been explained, the next step is to develop a methodology to estimate the concentrations of carbon monoxide, carbon dioxide, hydrocarbons and each HAP that will be found in the exhaust of a F-16 using JP-8 fuel at the different power settings. Because of the absence of data for exhaust sampling of the F-16 using JP-8 fuel, the only method available to develop the concentration of HAPs is to use past emission studies using differences in engine and fuel types to estimate logically HAP emissions for JP-8 fuel and the F-16 aircraft/F110 engine.

Data is generally considered to be useful only if two fuels were tested on the same engine in a controlled manner or where a significant number of engines were examined on each fuel (Fuels Branch, 1976:15), and this data is available from the previous studies. Thus, it can be used to propose concentrations of constituents for JP-8 fuel. In order to propose concentrations for HAPs, CO, C_xH_y, and CO_2, for the F110 engine on JP-8 fuel, there are two variables which must be addressed, engine type and fuel type. Differing engine type and fuel type have been shown to have an impact on aircraft emissions.

Engine Type. The type of engine in the aircraft will impact the concentration of emissions. Normally, newer model engines have much lower organic emissions than older model engines because of the improved combustion efficiency. The F110 engine is a newer engine. Although there are numerous engine parameters that can affect emissions,

24

the four which are the most important are: fuel/air ratio, engine speed, combustor inlet temperature, and combustor operating pressure.

Fuel/air ratio is one of the most important engine parameters affecting exhaust emission concentrations because it is directly related to combustion efficiency. Combustion efficiency is shown to fall off rapidly as the fuel/air ratio is lowered below a value of approximately .01. This effect is attributed to poor fuel atomization and reduced fuel penetration, because at low fuel flows the pressure drop across the fuel nozzle is too low to provide effective fuel atomization which causes larger droplets to form; thus, there is more time required for vaporization while the reduced fuel penetration results in ineffective mixing of the fuel and air (Grobman 1972:287). As combustion efficiency and fuel/air ratio is lowered, the emissions of hydrocarbons and carbon monoxide increases. Both fuel/air ratio and combustion efficiency are both related to engine speed.

Emission concentration is markedly reduced at higher engine speeds. This is because the increase in speed improves the combustion process by increasing turbulent mixing. In addition, the increased exhaust port turbulence at higher speeds promotes exhaust system oxidation reactions through better mixing (Patterson and Heinein 1972:149). Although speed has been shown to have negligible effect on carbon monoxide emissions, the concentration of hydrocarbon emissions decrease as speed is increased. Consequently, fuel/air ratios and combustion efficiencies normally increase with increasing engine speed.

Military aircraft engines operate in the idle, taxi, take-off, cruise, approach and afterburner(fighter aircraft only) modes. These modes are normally represented by a percentage equivalent. For example, the F110 engine emission concentrations have been tested at idle, 30% power, 63% power, intermediate and afterburner. As the engine power setting is increased above idle, the combustion efficiency is increased to near optimum levels. Consequently, the hydrocarbons drastically increase above this level. Table 3-2 illustrates this concept for a B-52D aircraft/J57 engine operating on JP-4 fuel.

Military fighter aircraft have an additional engine operating mode above 100% power. This mode is called afterburner. Since the F-16 aircraft is a fighter aircraft, an emission factor will also be required for the afterburner mode. Afterburner involves the injection and combustion of fuel in the exhaust gases exiting the non-afterburning section of the engine. Since only 15%-35% of available oxygen is used in the combustor, the rest remains for combustion in the afterburner (Blazowski and Henderson, 1972:10). The afterburner has a significant effect on pollutant emissions especially carbon monoxide and

Table 3-2

Hydrocarbon Emissions for B-52D Aircraft/J57 Engine (JP-4 Fuel)

Engine Operating Mode	Hydrocarbon Emissions (ppmC)
Idle	444.2
30% Thrust	27.6
75% Thrust	8.4

(AESO 1990B:21)

hydrocarbons (Sousa and Scott, 1978:9). General trends indicate significant emissions of CO and C_xH_y especially at lower afterburner power settings (Blazowski and Henderson, 1972:10).

The combustor inlet temperature also has an effect on the exhaust emissions. Normally, the hydrocarbon and carbon monoxide emissions increase with reduced combustor inlet total temperature (Grobman, 1972:290). However, although the emissions of hydrocarbons and carbon monoxide increase with decreasing combustor inlet total temperature, combustion efficiency does not appear sensitive to varying inlet total temperature.

The final engine parameter which has a strong impact on exhaust emissions is the combustor inlet total pressure. Hydrocarbon emissions are shown to increase as the combustor inlet total pressure is lowered (Grobman, 1972:289). Conkle et al. showed that the overwhelming effect of increasing combustor operating pressure was a large reduction in exhaust total hydrocarbon content (approximately six fold for each 2.2 increase in operating pressure) (1976:10). This was probably due to increased combustion efficiency resulting from both an increase in combustion temperature and pressure.

The four engine parameters discussed above will have an impact on the level of emissions. However, research shows that engine design does not influence the concentration of each constituent in the exhaust gas as much as fuel composition does (AESO 1990 :3).

Fuel Type. The type of fuel used will result in different levels of emissions. The DoD uses three fuels JP-4, JP-5 and JP-8. JP-4 fuel is being phased out and replaced with JP-8 fuel. These three fuels and their important fuel properties are listed in Table 3-3. The differences among fuels which affect the combustion process are those characteristics which deal with vaporization. These characteristics are indicated by the parameters: vapor pressure at $100^{\circ}F$ and flashpoint (Fuels Branch, 1976:5).

Flashpoint is the temperature at which the equilibrium vapor/air mixture above the liquid fuel surface reaches the lower limit at which flammability may occur. From Table 3-3, it can be seen that JP-4 has the highest vapor pressure so its flashpoint is at a much lower temperature. A lower flashpoint also indicates that the fuel is more volatile. The volatility of JP-4 is the main reason the Air Force is converting to JP-8 in their aircraft. JP-5 and JP-8 fuels are both much less volatile; JP-5 is used by the Navy. However, the effect of low volatility is that the liquid fuel vaporization rates in the combustor are reduced and thus, the time available for combustion reaction is lowered (Fuels Branch, 1976:5). Therefore, combustion efficiency is lowered and carbon monoxide and

hydrocarbon emissions are increased. For this reason, JP-5 and JP-8 can be expected to have higher carbon monoxide and hydrocarbon emissions.

Emission testing on the T-56 aircraft showed that compared to JP-4, the total concentration of exhaust hydrocarbons was greater with JP-5 and JP-8 which appears to show a relationship between exhaust content and fuel density and/or boiling range (Conkle et al., 1975:6). Since JP-5 and JP-8 have higher boiling points and densities, the hydrocarbon exhaust from these fuels can be expected to be higher. Conkle's study also found that there were qualitative differences between the fuels regarding olefins and ketones. Both of these increased with increasing fuel number perhaps suggesting a relationship with density. However, paraffins and aromatic content decreased and offset the increase in olefins and ketones.

Table 3-3

Characteristics of DoD Jet Fuels

	JP-4 Typical Value	JP-5 Typical Value	JP-8 Typical Value
Vapor Pressure @ 100°F (psi)	2.7	.05	.1
Initial Boiling Pt (°F)	140	360	335
End Boiling Pt (°F)	475	500	510
Flash Point (°F)	-10	145	125
Aromatic Content (% Volume)	12	16	16
Olefinic Content (% Volume)	1	1	1
Saturates Content (% Volume)	87	83	83
Net Heat of Combustion (BTU/lb)	18,700	18,500	18,600
Specific Gravity	.758	.818	.810

(Fuels Branch, 1976)

Whenever a fuel is burned, the emissions can be categorized into cracking or partial oxidation products and unburned fuel. Cracking or partial oxidation products result from reactions which take place in the combustion process itself and are not found in the original fuel. Unburned fuel is fuel that fails to combust, and thus, becomes part of the emissions. It has been shown that the cracking or partial oxidation products emissions do not seem to appear to be affected by fuel type; however, the unburned fuel distribution is affected by fuel type (Spicer et al., 1984:88). The make-up of JP-4 and JP-8 fuel is shown respectively in Tables 3-4 and 3-5. By reviewing the original make-up of the fuel, it can be determined which HAPs were part of the original fuel and which came about as the result of the combustion process. Using this information, it can be determined if a different fuel type will result in different emission concentrations for each HAP.

Table 3-4

Chemical Composition of JP-4 Fuel

Compound ID	Area Percentage
2-Methylbutane	0.98
2-Methylpentane	2.41
3-Methylpentane	2.01
Methylcyclopentane	0.84
2,2,3-Trimethylbutane	0.07
Benzene	0.48
Cyclohexane	0.98
2-Methylhexane	5.14
2,3-Dimethylpentane	1.88
3-Methylhexane	6.63
3-Ethylpentane	0.93
2,2,4-Trimethylpentane	0.11
Methylcyclohexane	1.00
2,2-Dimethylhexane	0.47
Ethylcyclopentane	0.15
2,5-Dimethylhexane	0.68
2,4-Dimethylhexane	1.16
3,3-Dimethylhexane	0.3
2,3,4-Trimethylpentane	0.17

Compound ID	Area Percentage
Methylbenzene	1.57
2,3-Dimethylhexane	0.84
2-Methylheptane	0.09
4-Methylheptane	0.11
3-Methylheptane	3.31
3-Ethylhexane	1.01
1,1-Dimethylcyclohexane	0.05
trans-1,2-Dimethylcyclohexane	0.16
2,2-Dimethylheptane	0.10
2,4-Dimethylheptane	0.24
2,6-Dimethylheptane	0.21
2,5-Dimethylheptane	0.44
3,3-Dimethylheptane	0.15
Ethylbenzene	0.60
cis,trans,trans-1,2,4-Trimethylcyclohexane	0.09
m,p-Xylene	0.75
4-Methyloctane	0.49
3-Methyloctane	0.66
o-Xylene	0.87
cis-1-Ethyl-3-methylcyclohexane	0.11
Cumene	0.23
2,6-Dimethyloctane	0.21
3,4-Diethylhexane	0.29
1,3,5-Trimethylbenzene	0.50
1-Ethyl-2-methylbenzene	0.57
2-Methylnonane	0.21
3-Methylnonane	0.18
1,2,4-Trimethylbenzene	1.62
Isobutylbenzene	0.05
1,2,3-Trimethylbenzene	0.48
1-Methyl-3-isopropylbenzene	0.14
Indan	0.08
n-Butylcyclohexane	0.08
1-Methyl-3-propylbenzene	0.47
1,4-Diethylbenzene	0.33
n-Butylbenzene	0.11
1-Methyl-2-propylbenzene	0.25
4-Methyldecane	0.47
1,3-Dimethyl-4-ethylbenzene	0.29
2-Methyldecane	0.26
1,2-Dimethyl-4-ethylbenzene	0.46
1,2-Dimethyl-3-ethylbenzene	0.16
1-Ethyl-3-isopropylbenzene	0.13
1,2,3,5-Tetramethylbenzene	0.34

Compound ID	Area Percentage
2,6-Dimethyldecane	0.13
Tetralin	0.21
n-Pentylbenzene	0.05
Napthalene	0.30
1,4-Di-isopropylbenzene	0.10
2-Methylundecane	0.32
1,2,4-Triethylbenzene	0.13
n-Hexylbenzene	0.09
2-Methylnapthalene	0.23
1-Methylnapthalene	0.26
Butane	0.32
Pentane	0.82
Hexane	3.72
Heptane	7.26
Octane	3.04
Nonane	1.1
Decane	1.03
Undecane	1.92
Dodecane	2.42
Tridecane	2.17
Tetradecane	1.47
Pentadecane	0.63
Hexadecane	0.17
Heptadecane	0.05
Totals	79.45

Table 3-5

Chemical Composition of JP-8 Fuel

Compound ID	Area Percentage
n- Octane	0.53
C3 Cyclohexane	0.92
C2 Benzene	0.18
Methyloctane	0.24
Dimethylheptane	0.30
Methyloctane	0.48
C2 Benzene	0.14
C2 Cyclohexane	0.40
n-Nonane	1.94
Dimethyloctane	1.94

Compound ID	Area Percentage
C3 Benzene	0.85
Ethylmethylbenzene	1.36
Trimethylbenzene	0.33
C4 Cyclohexane	0.28
C5 Cyclopentane	0.51
n-Decane	4.87
Dimethylnonane	1.75
Methylpropylbenzene	1.20
Ethyldimethylbenzene	0.38
Methyldecane	0.88
C4 Benzene	2.47
C5 Benzene	1.28
n-Undecane	7.22
1234 Trimethylbenzene	0.58
Methyldecalin	1.39
C12 Isoparaffin	1.79
Methylundecane	2.98
C5 Cyclohexane	0.87
Tetralin	0.78
Napthalene	0.58
Dimethyldecane	1.69
n-Dodecane	6.03
Methyldodecane	5.62
C6 Cyclohexane	0.90
Methyltetralin	0.84
Dimethylundecane	1.69
n-Tridecane	5.17
Methyltridecane	1.69
Trimethyldodecane	1.77
Dimethylnapthalene	0.45
n-Tetradecane	4.07
n-Pentadecane	2.64
n-Hexadecane	0.90
n-Heptadecane	0.28
Totals	73.16

Note: Area percentages are corrected values from GC/MS analyses of LC fractions.

Method To Estimate F110 Engine Emissions Using JP-8 Fuel. The objective of this study is to propose emission factors for the nine selected HAPs, at each engine

operating mode. In order to calculate the emission factors, the variables in the equation must be identified. The variables which must be estimated for the F110 engine operating on JP-8 fuel are the mole fraction concentration of each HAP, carbon monoxide, carbon dioxide, and total hydrocarbons. As mentioned in the introduction to this chapter, the method which will be used to estimate HAP, CO, CO_2, and C_xH_y concentrations for the F110 engine operating on JP-8 fuel will be derived from data from previous studies.

The CFM-56 and TF-39 engine study is the only study which quantified the individual compounds in the exhaust for different fuels. Both the CFM-56 and the TF-39 engines have data for the same testing conditions; they were both tested on JP-5 fuel for all engine operating conditions and were tested on JP-4 and JP-8 fuel at idle. However, the engine design for these two engines are different. In order to make the proposed concentrations for the F110 engine operating on JP-8 fuel more plausible, only data from the CFM-56 engine will be used because the CFM-56 engine design is much more similiar to the F110 engine than is the TF-39 engine. Table 3-6 compares the four engines in the studies by listing some important engine parameters. Although complete information is not provided for the CFM-56 engine, the core engine of the CFM-56 is essentially the same as that of the F101 engine (Spicer et al, 1984:9). It can be seen from the table that the F110 engine is closely related to the F101 engine for most parameters. Thus, the CFM-56 engine should be much more similar to the F110 engine than would the TF-39 engine. The TF-39 engine is a much larger engine with much more thrust. Additionally, the TF-39 engine is the only engine of the four which does not contain emission abatement devices. Thus, the emissions from this engine can be expected to be much higher. Because of the closer resemblance of the CFM-56 engine to the F110 engine, only the data from the CFM-56 engine will be used in estimating the F110 HAP emissions using JP-8 fuel.

There are two methods which will be used to propose the necessary concentrations in order to calculate the HAP emission factors. By using two methods, a range of values can

Table 3-6

Engine Comparison (Aircraft/Engine)

Engine Parameter	C-5 A,B/ TF-39 Engine	KC-135/ CFM-56 Engine	B-1B/ F101 Engine	F-16 C&D/ F110 Engine
Turbine Inlet Temperature	2300° F	-	>2500° F	2800° F
Compression Ratio	25:1	-	27:1	32:1
Thrust	41,000 lbt	24,000 lbt	17,000 lbt	29,000 lbt
Engine Weight	7,400 lb	-	4,000 lb	3,940 lb
Emission Abatement Device	N	Y	Y	Y

lbt- refers to lbs thrust   (Treager, 1979: 39,45) and (ASC,1992)

be developed for each HAP at each engine operating cycle.

Method 1

The first method will begin with data from the KC-135 aircraft/CFM-56 engine. As can be seen from Figure 3-2, concentrations are known for all engine operating conditions for JP-5 fuel, but are unknown for JP-4 and JP-8 fuel at 30% and 80% thrust (unknowns are represented by variables A,B,C,D). Method 1 will use the following steps to estimate the HAP emissions for the F-16 C&D/F110 engine operating on JP-8 fuel:

Step (1) - Estimate the HAP concentrations of the KC-135/CFM-56 engine at 30% and 80% thrust for JP-4 and JP-8 fuels (variables A-D).

This step will be accomplished by using two assumptions. The first assumption is that the HAP emissions for JP-8 fuel will be the same as those for JP-5 fuel. This is based on the similar make-up of the two fuels. From Table 3-3, it can be seen that the key characteristics of JP-5 and JP-8 are almost the same. Using this assumption, variable C will be the same as the known value for JP-5 at 30% thrust, and variable D will be the same as the known value for JP-5 at 80% thrust.

Figure 3-2

Process to Estimate F-16 C&D/F110 Engine Emissions for JP-8 Fuel - Method 1
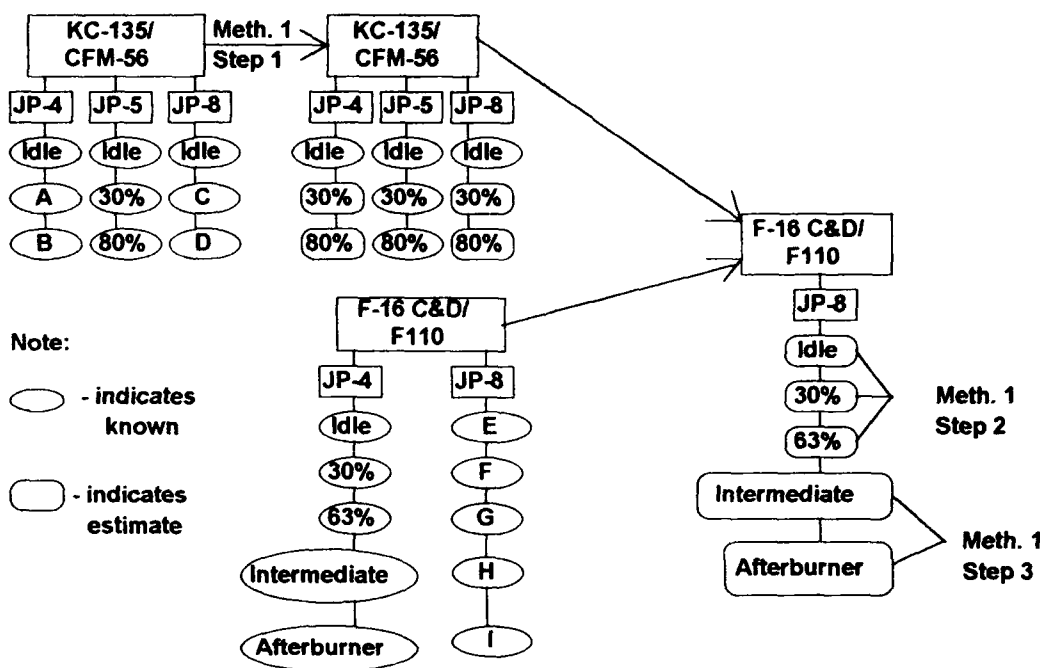
JP-4 fuel is much different than both JP-5 and JP-8 fuels. Thus, a different assumption must be used to estimate the HAP concentrations for variables A and B. The second assumption is that the % change in emissions for JP-5 from idle to a higher engine power mode will be the same for JP-4 fuel because the fuels are being burned in the same engine.

35

This assumption is reasonable if the key engine operating parameters (fuel/air ratio, combustion temperature, combustor operating pressure) are the same regardless whether JP-4 or JP-5 is combusted. Using this assumption, the % change in emissions for JP-5 from idle to 30% thrust can be found because both values are already known. Also, HAP concentrations at idle for JP-4 are also known. Thus, by assuming that the % change in emissions from idle to 30% for JP-5 fuel will be the same for JP-4 fuel, the HAP concentrations for JP-4 fuel at 30% thrust can be estimated by the following equation:

$$A = \left(\frac{CFM-56 / 30\% / JP-5}{CFM-56 / idle / JP-5} \right) \bullet \left(CFM-56 / idle / JP-4 \right)$$

The terminology (Engine type/Engine operating mode/Fuel type) will be used to refer to HAP concentration at a specific engine mode and a specific fuel. Since values for all three engine modes on the right side of the equation are known, a value for variable A can be estimated. Variable B can be found by using the same equation by substituting 80% thrust in for 30% thrust in the above equation. The estimated concentrations for variables A-D are shown in Figure 3-2 by replacing A-D with the respective engine operating modes.

Step (2) - Estimate the HAP emissions for variables E, F, and G for the F-16 C&D/F110 engine operating on JP-8 fuel by using the estimated concentrations of the CFM-56 engine (found in Step 1) and the known HAP concentrations of the F110 engine operating on JP-4 fuel.

Figure 3-2 shows the unknown variables E, F, and G which represent idle, 30% and 63% thrust respectively for the F110 engine operating on JP-8 fuel. To estimate variables E, F and G, the assumption will be used that the % change in HAP emissions from JP-4 to JP-8 fuel for the CFM-56 engine will be the same as the % change from JP-4 to JP-8 for the F110 engine because of the similarity of engines.

Step 1 already used the assumption that the % change in HAP emissions from JP-4 to JP-8 in the same engine should be approximately the same. The assumption in this step is based on the theory that the % change in emissions from JP-4 to JP-8 for the CFM-56 and for the F110 engine should be the same because of similar engine design. Although the actual HAP concentrations may be considerably different for the two engines, the % change from JP-4 to JP-8 should be the same in both engines. Using this assumption, variable E can be estimated using the following equation:

$$E = \left(\frac{CFM-56 \,/\, idle \,/\, JP-8}{CFM-56 \,/\, idle \,/\, JP-4} \right) \bullet \left(F110 \,/\, idle \,/\, JP-4 \right)$$

The CFM-56 values in the above equation were estimated in Step 1, and the F110 value is known from a past study. Thus, variable E can be estimated. Variables F and G will be estimated using the same assumption. For variable F:

$$F = \left(\frac{CFM56 \,/\, 30\% \,/\, JP-8}{CFM56 \,/\, 30\% \,/\, JP-4} \right) \bullet \left(F110 \,/\, 30\% \,/\, JP-4 \right)$$

But CFM56/30%/JP-8 = CFM-56/30%/JP-5 resulting in:

$$F = \left(\frac{CFM56 \,/\, 30\% \,/\, JP-5}{CFM56 \,/\, 30\% \,/\, JP-4} \right) \bullet \left(F110 \,/\, 30\% \,/\, JP-4 \right)$$

Since the denominator in the above equation represents variable A, substituting the expression for variable A results in:

$$F = \left(\frac{CFM56 \,/\, 30\% \,/\, JP-5}{\dfrac{CFM56 \,/\, 30\% \,/\, JP-5}{CFM56 \,/\, idle \,/\, JP-5} \bullet CFM56 \,/\, idle \,/\, JP-4} \right) \bullet \left(F110 \,/\, 30\% \,/\, JP-4 \right)$$

$$F = \left(\frac{CFM56 \,/\, idle \,/\, JP-5}{CFM56 \,/\, idle \,/\, JP-4} \right) \bullet \left(F110 \,/\, 30\% \,/\, JP-4 \right)$$

Using a similar derivation for variable G results in:

37

$$G = \left(\frac{CFM56 / idle / JP-5}{CFM56 / idle / JP-4} \right) \bullet \left(F110 / 63\% / JP-4 \right)$$

Step 2 also makes the assumption that 63% thrust in the F110 engine is equivalent to 80% thrust in the CFM-56 engine. From Table 3-6, the CFM-56 engine has a thrust of 24,000 lbt or 19,200 lbt at 80% thrust. The F110 engine has a thrust of 29,000 lbt or 18,270 lbt at 63% thrust. Since their values are similar, the assumption seems valid.

Step (3) - Estimate HAP concentrations for intermediate and afterburner (variables H and I) for the F110 engine operating on JP-8 fuel.

Variables H and I cannot be estimated in the same manner as Step 2 because these engine operating modes do not exist for the CFM-56 engine. Thus, variables H and I will be estimated by assuming the % change from JP-4 fuel to JP-8 fuel at idle for the F110 engine will be the same for intermediate and afterburner. Using this assumption, variable H can be found using the following equation:

$$H = \left(\frac{F110 / idle / JP-8}{F110 / idle / JP-4} \right) \bullet \left(F110 / intermediate / JP-4 \right)$$

or

$$H = \left(\frac{E}{F110 / idle / JP-4} \right) \bullet \left(F110 / intermediate / JP-4 \right)$$

where variable E = F110/idle/JP-8. Substituting the expression for variable E from Step 2 results in:

$$H = \left(\frac{CFM56 / idle / JP-8}{CFM56 / idle / JP-4} \right) \bullet \left(F110 / intermediate / JP-4 \right)$$

Using a similar derivation for variable I results in:

$$I = \left(\frac{CFM56 / idle / JP-8}{CFM56 / idle / JP-4} \right) \bullet \left(F110 / afterburner / JP-4 \right)$$

Method 2

Method 2 will estimate HAP concentrations differently than method 1. Method 2 ignores the known concentrations of the KC-135/CFM-56 engine for JP-5 for all engine

Figure 3-3

Process to Estimate F-16 C&D/F110 Engine Emissions for JP-8 Fuel - Method 2
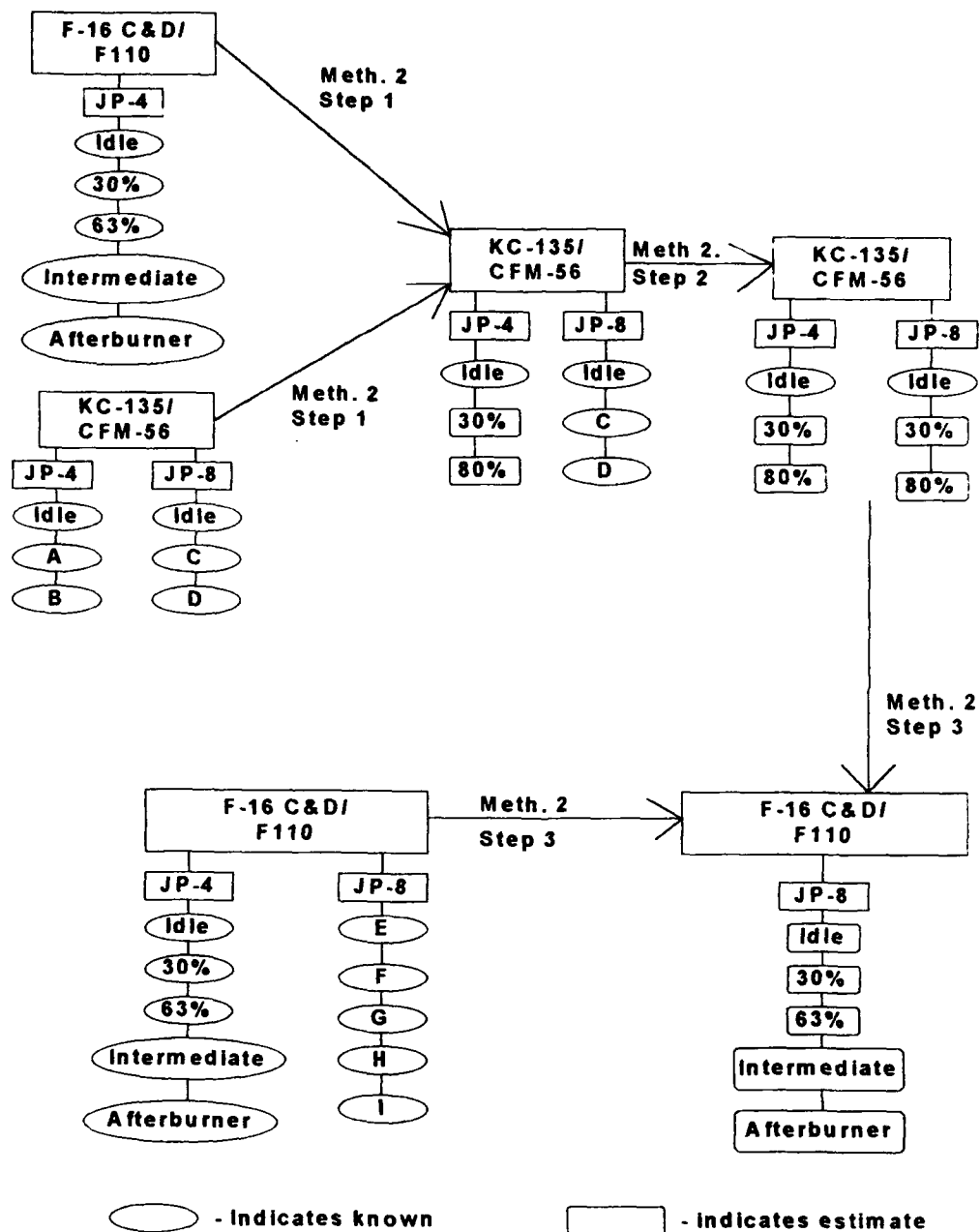
operating modes and instead focuses on JP-4 and JP-8 fuels in both the CFM-56 and F110 engines. Figure 3-3 shows a flow diagram of the process. The following steps will be used to ultimately estimate the HAP emissions for the F-16C&D/F110 engine operating on JP-8 fuel:

Step (1) - Estimate the HAP concentrations at 30% and 80% thrust for the CFM-56 engine for JP-4 fuel (variables A and B) by using the known HAP concentrations of the CFM-56 engine for JP-4 fuel at idle and the known HAP concentrations of the F110 engine for JP-4 fuel at all engine operating modes.

Variables A can be estimated by assuming that the % change in HAP emissions from idle to 30% in the F110 engine will be the same from idle to 30% for the CFM-56 engine. This assumption is again based on similar engine design between the two engines. Since the HAP concentrations are already known for idle and 30% thrust for the F110 engine using JP-4 fuel and for idle for the CFM-56 engine using JP-4 fuel, Variable A can be estimated using the following equation:

$$A = \left(\frac{F110 / 30\% / JP - 4}{F110 / idle / JP - 4} \right) \bullet (CFM - 56 / idle / JP - 4)$$

Variable B (80% thrust/JP-4 fuel) can be found using the same equation but substituting (F110/63%/JP-4) in place of (F110/30%/JP-4). The estimates for variables A and B are indicated in Figure 3-3 by replacing the variables with their respective thrusts.

Step (2) - Estimate the HAP concentrations for the CFM-56 engine at 30% and 80% thrust using JP-8 fuel (variables C and D) by using the estimated concentrations found in Step 1.

The same assumption will be used to perform this step that was used to find variables

A and B in Step 1 of method 1. The assumption is that the % change of HAP emissions from idle to 30% and idle to 80% for JP-4 fuel will be the same for JP-8 fuel based on both fuels being burned in the same engine. Since HAP concentrations for the CFM-56 engine at idle for JP-4 and JP-8 are already known and the HAP concentration at 30% for JP-4 (variable A) was estimated in Step 1, variable C can be estimated by the following equation:

$$C = \left(\frac{CFM -56 / 30\% / JP -4}{CFM -56 / idle / JP -4} \right) \bullet \left(CFM -56 / idle / JP -8 \right)$$

Variable D can be estimated by using the same equation but substituting (CFM-56/80%/JP-4) in place of (CFM-56/30%/JP-4). The estimated values for variables C and D are indicated in Figure 3-3 by replacing the variables with 30% and 80% thrust respectively.

Step (3) - Estimate the HAP concentrations for variables E, F, and G for the F110 engine operating on JP-8 fuel for all engine operating modes by using the estimated concentrations of the CFM-56 engine for JP-4 and JP-8 fuels (Steps 1 and 2) and the known concentrations of the F110 engine operating on JP-4 fuel for all engine operating modes.

Since HAP concentrations have been estimated for all engine operating modes of the CFM-56 engine for JP-4 and JP-8 fuels and are already known for the F110 engine operating on JP-4 fuel, the same information is available which was available in Step 2 of method 1. Thus, the same process and same assumption can be used to estimate the HAP emissions for variables E, F and G. This results in:

$$E = \left(\frac{CFM56 / idle / JP -8}{CFM56 / idle / JP -4} \right) \bullet \left(F110 / idle / JP -4 \right)$$

$$F = \left(\frac{\text{CFM56 / 30\% / JP} -8}{\text{CFM56 / 30\% / JP} -4} \right) \bullet \left(\text{F110 / 30\% / JP} -4 \right)$$

$$G = \left(\frac{\text{CFM56 / 80\% / JP} -8}{\text{CFM56 / 80\% / JP} -4} \right) \bullet \left(\text{F110 / 63\% / JP} -4 \right)$$

Note that variables F and G differ from Method 1 in that the numerator uses CFM56/30%/JP-8 instead of CFM56/30%/JP-5). This is because Method 2 ignores the JP-5 data for the CFM56 engine.

Step (4) - Estimate the HAP concentrations for intermediate and afterburner (variables H and I) for the F110 engine operating on JP-8 fuel.

Variables H and I will be estimated by the same method as method 1 because these engine operating modes do not exist for the CFM-56 engine. Thus:

$$H = \left(\frac{\text{CFM56 / idle / JP} -8}{\text{CFM56 / idle / JP} -4} \right) \bullet \left(\text{F110 / intermediate / JP} -4 \right)$$

$$I = \left(\frac{\text{CFM56 / idle / JP} -8}{\text{CFM56 / idle / JP} -4} \right) \bullet \left(\text{F110 / afterburner / JP} -4 \right)$$

Method 1 and 2 Differences The differences between the two methods are in the procedures used to estimate concentrations for JP-4 and JP-8 in the CFM-56 engine (variables A-D). In Method 1, the known concentration of JP-5 fuel in the CFM-56 engine was used to estimate the concentrations (above idle) for JP-4 and JP-8. However, Method 2 uses the known concentrations of the F110 engine using JP-4 fuel for all engine operating conditions to first estimate the JP-4 emissions for the CFM-56 engine. JP-8 HAP emissions for the CFM-56 engine is estimated once JP-4 has been estimated. Note that once the concentrations have been proposed for the CFM-56 engine using all fuels for all engine operating conditions, both methods use the same procedures to ultimately estimate JP-8 HAP emissions for the F110 engine.

Estimation of CO, C_xH_y, and CO_2

The remaining variables to determine for use in the equation for the emission factor are the mole fraction concentrations of CO, C_xH_y, and CO_2 in the exhaust. Estimates of these concentrations for the F-16 C&D aircraft/F110 engine using JP-8 fuel must be accomplished. To estimate these concentrations, the same two methods which were used for HAPs will be used. The same data is available from both the F110 and CFM-56 engines for CO, C_xH_y, and CO_2; the CFM-56 engine has data using JP-5 fuel for all engine operating conditions and has data using JP-8 and JP-4 for idle while the F110 engine data is available for idle for JP-4 fuel.

In estimating individual HAP emissions, the assumption was used that JP-8 fuel emissions would be approximately the same as JP-4 fuel HAP emissions based on the si..:lar make-up of the fuels. However, this assumption will not be used in estimating total hydrocarbon and carbon monoxide emissions for JP-8 fuel. Instead the finding in Conkle et al's 1975 study that emissions tend to increase with increasing fuel number will be used. Consequently, both JP-4 and JP-8 emissions for total hydrocarbons, carbon monoxide, and carbon dioxide will use the % difference in HAP emissions as a result of fuel type differences which were used in step 1 of method 1 and step 2 of method 2.
The data from the studies described in the methodology, along with the estimated concentrations and emission factors for the F-16 C&D aircraft/F110 engine are presented in Chapter 4.

Emission Inventory for Airfield Operation

Since an emission factor has been estimated for each HAP at each engine operating condition, it is possible to develop an emission inventory for an airfield operation for F-16 C&D aircraft.

In order to determine a HAP inventory for the F-16 C&D aircraft, HAP emissions will need to be found for each portion of a F-16 sortie (mission). Once HAP emissions are found for each portion of the mission, they can be summed up to find total emissions for the particular HAP. This process will be done for each HAP.

The following equation will be used to calculate the emissions from each portion of the mission:

$$W = N \bullet F \bullet t \bullet e$$

where N = number of engines

F = fuel flow (kg/s)

t = time in engine mode (seconds)

e = emission factor (g HAP/kg fuel)

W = total HAP emissions (g)

This equation will be used for each portion of the mission. A typical F-16 mission has eleven stages. These mission modes, along with the engine modes and time in mode for each portion of the mission, are shown in Appendix A. These values were taken from the 1985 study by Seitchek et al. In the above equation, the fuel flow and emission factor will be for the engine operating mode which corresponds to that portion of the mission. For example, the first mission mode is known as start-up. During this portion of the mission, the engine operates at idle. Thus, the fuel flow at idle and the HAP emission factor at idle will be substituted into the equation. However, the time in engine mode variable (t) refers to the time required for the portion of the mission to take place. Thus, for the start-up portion of the mission, the time required for start-up is substituted into the equation. Another way to write the equation is:

$$W(\text{mission mode}) = N \bullet F(\text{engine mode}) \bullet t(\text{mission mode}) \bullet e \, (\text{engine mode})$$

The information derived from the Seitchek et al. study, along with the estimated emission factors for each HAP at each engine mode, will provide the necessary information to compile a HAP emission inventory for an F-16 airfield operation.

Aircraft operations can be divided into two types: landings and take-offs (LTOs) or flying mission and touch and gos (TGOs) or practice landings and takeoffs (Fagin, 1988:22). Consequently, the HAP emission inventory should consist of both LTO and TGO operations. However, TGO operations are only performed in certian situations because they can damage the wheels of the F-16 (Freisner, 8 Jun 94). Thus, only LTO operations will be used for the HAP emission inventory. The HAP emission inventory is provided in Appendix A to this thesis.

4. Data and Analysis

The following data shown in Tables 4-1 and 4-2 for the nine selected HAPs is available from past studies. The data was taken from the 1984 Spicer et al. study on the KC-135 aircraft/CFM-56 engine (Table 4-1) and the 1990 Spicer et al. study on the F-16 C&D aircraft/F110 engine (Table 4-2).

Table 4-1

CFM-56 Engine Data

HAP	Fuel Type	Engine Modes (ppmC)		
		Idle	30%	80%
Formaldehyde	JP-4	9.3	-	-
Formaldehyde	JP-5	13.1	.077	.17
Formaldehyde	JP-8	13.3	-	-
Benzene	JP-4	1.95	-	-
Benzene	JP-5	3.27	.02	.02
Benzene	JP-8	3.84	-	-
Toluene	JP-4	1.26	-	-
Toluene	JP-5	1.23	.01	ND
Toluene	JP-8	1.44	-	-
1,3-Butadiene	JP-4	2.10	-	-
1,3-Butadiene	JP-5	3.17	ND	.01
1,3-Butadiene	JP-8	3.91	-	-
m&p-Xylene	JP-4	1.25	-	-
m&p-Xylene	JP-5	.53	ND	ND
m&p-Xylene	JP-8	.68	-	-
o-Xylene	JP-4	.54	-	-
o-Xylene	JP-5	.31	ND	.01
o-Xylene	JP-8	.42	-	-
Ethylbenzene	JP-4	.45	-	-
Ethylbenzene	JP-5	.32	ND	ND
Ethylbenzene	JP-8	.44	-	-
Acetaldehyde	JP-4	2.10	-	-
Acetaldehyde	JP-5	6.20	.03	.041
Acetaldehyde	JP-8	5.50	-	-
Acrolein	JP-4	2.4	-	-
Acrolein	JP-5	4.2	<.01	<.01
Acrolein	JP-8	3.8	-	-

(Adapted from Spicer et al., 1984)

ND - indicates non- detection of HAP at respective engine thrust

46

Table 4-2

F110 Engine Data

HAP	Fuel	Engine Mode (ppmC)				
		Idle	30%	63%	Intermediate	Afterburner
Formaldehyde	JP-4	.305	.162	.095	.090	9.942
Benzene	JP-4	.079	.023	.017	.011	5.544
Toluene	JP-4	.985	.032	.012	.007	6.949
1,3-Butadiene*	JP-4	.034	.016	.016	.009	5.429
m&p-Xylene	JP-4	.086	.021	.006	.003	4.813
o-Xylene	JP-4	.030	.007	.002	.001	1.410
Ethylbenzene	JP-4	.024	.006	.002	.001	1.393
Acetaldehyde	JP-4	.140	.080	.042	.032	.704
Acrolein	JP-4	.015	<.001	.009	.003	3.222

*- Indicates 1,3-Butadiene & 1-Butene   (Adapted from Spicer et al., 1990)

This data will be used to estimate the concentrations of HAPs at all engine operating conditions for the F-16 C&D/F110 engine operating on JP-8 fuel. The final concentrations will be estimated using the two methods discussed in the methodology. Within this section, the reference to an engine, its thrust and its fuel type will be indicated by: engine type/thrust/fuel type.

Method 1

Table 4-1 shows the concentrations of the nine HAPs for the KC-135/CFM-56 engine. The first step of method 1 is to estimate the HAP concentrations for 30% thrust and 80% thrust for JP-4 and JP-8 fuels (Variables A-D). Using the assumption discussed in Chapter 3, pages 34-35 that JP-8 and JP-5 fuel should have approximately the same exhaust concentrations for each HAP, variable C will be equal to the HAP concentration of the CFM-56 engine/30%/JP-5, and variable D will be equal to the HAP concentration of the CFM-56 engine/80%/JP-5. This assumption seems valid by analyzing the data found in Table 4-1 for each HAP at idle. As can be seen, the concentrations for each HAP at idle for JP-5 and JP-8 fuel are very similar for all HAPs.

Variables A and B (30% and 80% thrust for JP-4 fuel) can be found using the assumption that the % change in emissions from JP-5 to JP-4 will be approximately the same. Thus, variable A can be calculated by the following formula:

$$(1) \quad A = \left(\frac{CFM -56 / 30\% / JP -5}{CFM -56 / idle / JP -5} \right) \bullet \left(CFM -56 / idle / JP -4 \right)$$

Likewise, variable B can be found using equation (1) but substituting the 80% thrust concentration in for 30%. To find variable A for formaldehyde, substitute the appropriate values from Table 4-1 into equation (1). This results in:

$$A = \left(\frac{.077}{13.1} \right) \bullet (9.3) \quad = .055 \text{ ppmC formaldehyde}$$

The remaining appropriate values from Table 4-1 can be substituted into the equation to find estimated values for variables A and B for each HAP. The estimated concentrations for variables A-D for each HAP is shown in Table 4-3. This table is a revised version of Table 4-1.

Note that ND appears frequently for HAP concentrations above idle. This indicates that the compound was present in such small amounts that it was not detected. Thus, the assumption made was that the same concentration (ND) would be found for JP-4 and JP-8 fuels. Also, acrolein at both 30% and 80% thrust was measured at less than .01 ppmC. The same amounts were also assumed for JP-4 and JP-8 fuels.

The next step is to use the HAP concentrations from Table 4-3 and compare them to the known concentrations for the F-16 C&D aircraft/F110 engine operating on JP-4 fuel. By comparing exhaust emissions for both engines, HAP emissions can be estimated for the F110 engine operating on JP-8 fuel.

To find variables E, F, and G (idle, 30% thrust, 63% thrust for the F110 engine using JP-8 fuel) for each HAP, the same process is used. For example, to find the estimated

Table 4-3

HAP Concentrations for CFM-56 Engine for JP-4/JP-5/JP-8 Fuels

HAP	Fuel Type	Engine Modes (ppmC)		
		Idle	30%	80%
Formaldehyde	JP-4	9.3	.055*	.121*
Formaldehyde	JP-4	13.1	.077	.170
Formaldehyde	JP-8	13.3	.077*	.170*
Benzene	JP-4	1.95	.012*	.012*
Benzene	JP-5	3.27	.02	.02
Benzene	JP-8	3.84	.02*	.02*
Toluene	JP-4	1.26	.01*	ND*
Toluene	JP-5	1.23	.01	ND
Toluene	JP-8	1.44	.01*	ND*
1,3-Butadiene	JP-4	2.1	ND*	.007*
1,3-Butadiene	JP-5	3.17	ND	.01
1,3-Butadiene	JP-8	3.41	ND*	.01*
m&p-xylene	JP-4	1.25	ND*	ND*
m&p-xylene	JP-5	.53	ND	ND
m&p-xylene	JP-8	.68	ND*	ND*
o-xylene	JP-4	.54	ND*	.02*
o-xylene	JP-5	.31	ND	.01
o-xylene	JP-8	.42	ND*	.014*
Ethylbenzene	JP-4	.45	ND*	ND*
Ethylbenzene	JP-5	.32	ND	ND
Ethylbenzene	JP-8	.44	ND*	ND*
Acetaldehyde	JP-4	2.1	.01*	.014*
Acetaldehyde	JP-5	6.2	.03	.041
Acetaldehyde	JP-8	5.5	.03*	.041*
Acrolein	JP-4	2.4	<.01*	<.01*
Acrolein	JP-5	4.2	<.01	<.01
Acrolein	JP-8	3.8	<.01*	<.01*

* - indicates an estimated concentration using equations (1) and (2)

HAP concentration for variable E the following formula is used:

$$(2) \qquad E = \left(\frac{CFM -56 / idle / JP -8}{CFM -56 / idle / JP -4} \right) \bullet \left(F110 / idle / JP -4 \right)$$

Likewise, variables F and G can be found using the respective equations found on page 37. To find variable E for formaldehyde, substitute the appropriate values from Tables 4-2 and 4-3 into equation (2):

$$E = \left(\frac{13.3}{9.3}\right) \bullet (.305) = .436 \text{ ppmC formaldehyde}$$

The remaining values from Tables 4-2 and 4-3 can be substituted into the equation resulting in the estimated concentrations for variables E, F and G for each HAP for the F110 engine using JP-8 fuel. These estimated concentrations are shown in Table 4-4.

Note that several of the HAPs estimated values for 30% and 63% are the same as the values for JP-4 fuel. This is because some of the HAP concentrations were ND (no detection) or <.001 (acrolein) for all three fuels. Thus, when equation (2) is used, these concentrations divide out to 1 leaving the concentration for JP-8 in the F110 engine to be equal to the concentration for JP-4 in the F110 engine. This assumption seems valid because the HAPs concentrations at these thrusts are very small.

Another assumption used was for the estimation of 1,3-butadiene. From Table 4-2, it can be seen that the concentration for 1,3-butadiene also contains 1-butene. Thus, it is necessary to estimate how much of this total concentration is solely 1,3-butadiene. From the 1984 Spicer et al. study on the KC-135/CFM-56 engine, separate concentrations were measured for both 1,3-butadiene and 1-butene for JP-4 at idle. These concentrations were 11.21 ppmC for 1-butene and 6.26 ppmC for 1,3-butadiene.

Using the assumption that the F110 and CFM-56 are similar engines, the % change in emissions for both compounds should be approximately the same in each engine. Since 11.26 ppmC is 1.8 times larger than 6.26 ppmC, the same ratios will be assumed for the F110 engine. The total must equal the value shown in Table 4-2 (.034 ppmC). Thus, the following equation can be used:

$$x + 1.8x = .034$$

where x = estimated concentration of 1,3-butadiene

1.8x = estimated concentration of 1-butene

Solving for x, the estimated concentration for 1,3 butadiene in the F110 engine operating on JP-4 fuel at idle is .012 ppmC. This value was used in equation (2). The same procedure is used to estimate 1,3 butadiene concentrations at 30%, 63%, intermediate and afterburner.

The last step is to estimate concentrations for variables H and I (intermediate and afterburner) for the F110 engine operating on JP-8 fuel. As mentioned in Chapter 3, page 38, variable H and variable I will be estimated using the assumption that the % change in emissions from JP-4 to JP-8 at idle in the F110 engine will be the same for intermediate and afterburner. Thus, variable H can be found by the following formula derived on page 38:

$$(3) \quad H = \left(\frac{\text{CFM56 / idle / JP} -8}{\text{CFM56 / idle / JP} -4} \right) \bullet \left(\text{F110 / intermediate / JP} -4 \right)$$

To find variable I for formaldehyde, substitute in the appropriate values for each operating mode:

$$H = \left(\frac{13.3}{9.3} \right) \bullet (9.947) = \quad \textbf{14.23 ppmC formaldehyde}$$

Table 4-4 shows the final estimated concentrations for the F-16 C&D/F110 engine operating on JP-8 fuel for each engine mode from method 1.

Method 2

Table 4-2 shows the known concentrations of the nine selected HAPs for the F-16 C&D/F110 engine for all engine operating conditions using JP-4 fuel. The first step is to find variable A and B using the assumption that the % change in HAP emissions from the F110 engine to the CFM-56 engine will be the same because of similar engine types.

Thus, to find variable A, the following equation is used:

$$(4) \quad A = \left(\frac{F110 / 30\% / JP -4}{F110 / idle / JP -4} \right) \bullet \left(CFM -56 / idle / JP -4 \right)$$

Table 4-4

Estimated HAP Concentrations for F-16 C&D/F110 Engine (JP-8 Fuel) - Method 1

HAP	Engine Modes (ppmC)				
	Idle	30%	63%	Intermediate	Afterburner
Formaldehyde	.436	.228	.134	.129	14.22
Benzene	.156	.039	.029	.022	10.92
Toluene	1.13	.031	.012	.008	7.94
1,3-Butadiene	.019	.009	.009	.005	3.15
m&p-xylene	.047	.009	.007	.002	2.62
o-xylene	.023	.004	.001	.001	1.10
Ethylbenzene	.023	.004	.001	.001	1.36
Acetaldehyde	.367	.236	.124	.084	1.84
Acrolein	.024	<.001	.016	.005	5.10

Variable B can be found for each HAP using the same equation except 63% thrust is substituted for 30% thrust. Variable A for formaldehyde can be found by substituting in the appropriate values from Tables 4-1, and 4-2 :

$$A = \left(\frac{.162}{.305} \right) \bullet (9.3) = 4.94 \text{ ppmC formaldehyde}$$

To find variables C and D, the assumption is used that the % change in emissions from JP-4 to JP-8 is the same because both fuels are being burned in the same engine. Variable C can be calculated using the following equation:

$$(5) \quad C = \left(\frac{CFM -56 / 30\% / JP -4}{CFM -56 / idle / JP -4} \right) \bullet \left(CFM -56 / idle / JP -8 \right)$$

Note that the numerator in the above equation is the same as variable A. Variable D can be found using equation (5) but substituting the appropriate value for 80% thrust in for

30% thrust (variable B) in the numerator. Variable C for formaldehyde can be found by substituting in the appropriate values:

$$C = \left(\frac{4.94}{9.3}\right) \bullet (13.3) \ = \ 7.06 \ \text{ppmC formaldehyde}$$

Values for variables A-D are shown in Table 4-5.

Table 4-5

HAP Concentrations for KC-135/CFM-56 Engine (JP-4 and JP-8)

HAP	Fuel Type	Engine Modes (ppmC)		
		Idle	30%	80%
Formaldehyde	JP-4	9.3	4.94*	2.90*
Formaldehyde	JP-8	13.3	7.06*	4.15*
Benzene	JP-4	1.95	.57*	.42*
Benzene	JP-8	3.84	1.12*	.83*
Toluene	JP-4	1.26	.04*	.02*
Toluene	JP-8	1.44	.05*	.02*
1,3-Butadiene	JP-4	2.1	1.05*	1.05*
1,3-Butadiene	JP-8	3.91	1.96*	1.96*
m&p-xylene	JP-4	1.25	.31*	.09*
m&p-xylene	JP-8	.68	.17*	.05*
o-xylene	JP-4	.54	.13*	.04*
o-xylene	JP-8	.42	.10*	.03*
Ethylbenzene	JP-4	.45	.11*	.04*
Ethylbenzene	JP-8	.44	.11*	.04*
Acetaldehyde	JP-4	2.1	1.2*	.63*
Acetaldehyde	JP-8	5.5	3.14*	1.65*
Acrolein	JP-4	2.4	.16*	1.44*
Acrolein	JP-8	3.8	.25*	2.28*

* - indicates estimated concentrations using equations (4) and (5)

The next step in method 2 is to compare the concentrations in Table 4-5 with the known concentrations of the F-16 C&D/F110 engine operating on JP-4 fuel using the assumption that % increase in HAP emissions from JP-4 to JP-8 is the same because of similar engine type.

53

To find variables E use equation (2), page 47 from method 1. Variables F and G can be calculated using the respective equations from page 41. To find variable E for formaldehyde , substitute the appropriate values from Tables 4-2 and 4-5 which results in:

$$E = \left(\frac{13.3}{9.3}\right) \bullet (.305) = .436 \text{ ppmC formaldehyde}$$

The estimated concentrations for variables E, F and G are presented in Table 4-6.

Intermediate and afterburner (variables H and I) are calculated the same as method 1 discussed on page 49. They will be calculated by assuming the % change in emissions from JP-4 to JP-8 for the F110 engine will be the same as at idle. Table 4-6 shows the values for variables H and I for each HAP.

Table 4-6

Estimated HAP Concentrations for F-16C&D/F110 Engine (JP-8 Fuel) - Method 2

HAP	Engine Modes (ppmC)				
	Idle	30%	63%	Intermediate	Afterburner
Formaldehyde	.436	.232	.136	.129	14.22
Benzene	.156	.045	.034	.022	10.92
Toluene	1.130	.040	.012	.008	7.94
1,3 Butadiene	.022	.011	.011	.005	3.15
m&p-xylene	.047	.012	.003	.002	2.62
o-xylene	.023	.005	.002	.001	1.10
Ethylbenzene	.023	.006	.002	.001	1.36
Acetaldehyde	.367	.209	.110	.084	1.84
Acrolein	.024	.002	.014	.005	5.10

Comparing Tables 4-4 and 4-6, the estimated concentrations from both methods are very similar. Idle is exactly the same because concentrations were already known for this engine mode for all three fuels in the CFM-56 engine and for JP-4 in the F110 engine. Thus, the estimates should be more exact. Intermediate and afterburner estimates were the same because since idle was the same for both methods, the % increase from idle to intermediate and afterburner will be the same. The only engine modes where differences

occurred were at 30% and 63% thrust. However, the concentrations were still very close to each other due to the small HAP concentrations found in the exhaust and because of the similar assumptions used in both methods.

Estimation of C_xH_y, CO, and CO_2

Tables 4-7 and 4-8 show the concentrations for C_xH_y, CO, and CO_2 from the KC-135/CFM-56 engine (Table 4-7) and the F-16 C&D/F110 engine (Table 4-8). These concentrations will be analyzed by the same two methods used for HAPs to estimate the concentrations for these values for the F110 engine operating on JP-8 fuel. Once these values are estimated, all the necessary information is available to develop an emission factor for each engine operating mode.

Table 4-7

C_xH_y, CO and CO_2 Concentrations for the KC-135/CFM-56 engine

Pollutant	Fuel Type	Engine Modes		
		Idle	30%	63%
C_xH_y (ppmC)	JP-4	119.5	-	-
CO (ppm)	JP-4	640.3	-	-
CO_2 (%)	JP-4	2.03	-	-
C_xH_y (ppmC)	JP-5	181.4	3.1	4.9
CO (ppm)	JP-5	770.0	50.6	ND
CO_2 (%)	JP-5	2.32	2.86	4.35
C_xH_y (ppmC)	JP-8	196.7	-	-
CO (ppm)	JP-8	758.2	-	-
CO_2 (%)	JP-8	2.11	-	-

(Spicer et al., 1984:38)

Table 4-8

C_xH_y, CO and CO_2 Concentrations for the F-16C&D/F110 engine (JP-4)

Pollutant	Engine Modes				
	Idle	30%	63%	Intermediate	Afterburner
C_xH_y (ppmC)	7.0	6.0	3.0	3.5	335.0
CO (ppm)	85.0	23.0	13.0	15.0	178.0
CO_2 (%)	.98	1.25	2.35	3.17	.41

(Spicer et al., 1990:27)

55

Method 1 Equation (1) will be used to estimate the concentrations of C_xH_y, CO, and CO_2 for variables A-D:

To find variable A: use equation (1) (see page 46)

To find variable B: change (CFM-56/idle/JP-5) in equation (1) to (CFM-56/80%/JP-5)

To find variable C: change (CFM-56/idle/JP-4) in equation (1) to (CFM-56/idle/JP-8)

To find variable D: make both changes used to find variables B and C

For example, to find C_xH_y for variable A, substitute the appropriate values from Tables 4-7 results in:

$$A = \left(\frac{3.1}{181.4}\right) \bullet (119.5) = 2.04 \text{ ppmC } C_xH_y$$

The concentrations for C_xH_y, CO, and CO_2 for variables A-D are shown in Table 4-9.

Table 4-9

C_xH_y, CO, and CO_2 Concentrations for CFM-56 Engine

Pollutant	Fuel Type	Engine Modes		
		Idle	30%	80%
C_xH_y (ppmC)	JP-4	119.5	2.04*	3.23*
C_xH_y (ppmC)	JP-5	174.6	3.1	4.9
C_xH_y (ppmC)	JP-8	196.7	3.36*	5.31*
CO (ppm)	JP-4	640.3	42.1*	ND*
CO (ppm)	JP-5	770.0	50.6	ND
CO (ppm)	JP-8	758.2	49.8*	ND*
CO_2 (%)	JP-4	2.03	2.50*	3.81*
CO_2 (%)	JP-5	2.32	2.86	4.35
CO_2 (%)	JP-8	2.11	2.60*	3.96*

ND - Indicates no detection
* - Indicates an estimated concentration

From Table 4-9, note that no CO was detected at 80% thrust for JP-5 fuel. Thus, the assumption will be used that the same concentration will occur for both JP-4 and JP-8 fuels.

The next step is to compare the concentrations from Table 4-9 with those from the F-16 C&D/F110 engine (Table 4-8) to estimate C_xH_y, CO, and CO_2 for all operating modes

of the F110 engine operating on JP-8 fuel. Variables E, F and G can be found using equation (2) the following ways:

For variable E: use equation (2) (see page 47).

For variable F: change engine modes in equation (2) from idle to 30%.

For variable G: change engine modes in equation (2) from idle to 80% for the CFM56 engine and to 63% for the F110 engine.

The concentrations for variables E-G for each pollutant are found in Table 4-10.

Variable H and variable I will again be calculated by assuming the % change in emissions at idle from JP-4 to JP-8 will be the same for intermediate and afterburner. Thus, equation (3), page 49 will again be used. For example to find the concentration of hydrocarbons at afterburner:

$$H = \left(\frac{11.52}{7}\right) \bullet (3.5) = 5.76 \text{ ppmC } C_xH_y$$

The same calculation can be used for CO and CO_2. The final estimated concentrations for C_xH_y, CO, and CO_2 for the F-16 C&D/F110 engine for all engine operating modes (JP-8 fuel) is shown in Table 4-10.

Note that CO at 63% thrust is assumed to be the same as CO concentration at 63% thrust for JP-4 fuel. This was done because CO was not detected at 80% thrust in the CFM-56 engine. This assumption seems valid because looking at Table 4-9, the CO

Table 4-10

Estimated Concentrations for C_xH_y, CO, and CO_2 for F-16 C&D/F110 Engine (JP-8) - Method 1

Pollutant	Engine Modes				
	Idle	30%	63%	Intermediate	Afterburner
C_xH_y (ppmC)	11.52	9.88	4.93	5.76	551.4
CO (ppm)	100.7	27.2	13*	17.76	210.8
CO_2 (%)	1.02	1.3	2.44	3.30	.43

* - indicates same concentration as JP-4 fuel

concentrations for JP-4 and JP-8 are much closer to each other at 30% thrust compared to idle. One would expect these values to be even closer at higher thrust.

Method 2 Equation (4), page 50 will be used to find the concentrations of variables A and B in the following way:

For variable A: use equation (4) (see page 50).

For variable B: change F110/30%/JP-4 in equation (4) to F110/63%/JP-4.

For example, variable A for C_xH_y can be found by substituting the values from Tables 4-7 and 4-8 resulting in:

$$A = \left(\frac{6}{7}\right) \bullet (119.5) = 102.4 \text{ ppmC } C_xH_y$$

The estimated concentrations for variables A and B for each pollutant are shown in Table 4-11.

To find variables C and D, use equation (5) in the following way:

For

variable C: use equation (5) (see page 50).

For variable D: change (CFM-56/30%/JP-4) in equation (5) to (CFM-56/80%/JP-4).

For example, substituting the appropriate values from Tables 4-7 and 4-8 for C_xH_y for variable C results in:

$$C = \left(\frac{102.4}{119.5}\right) \bullet (196.7) = 168.6 \text{ ppmC } C_xH_y$$

Values for variables C and D for each pollutant are shown in Table 4-1. The next step is to use the concentrations from Table 4-11 to compare against the known concentrations for the F110 engine using the assumption that the % change in emissions from JP-4 to JP-8 is the same because of similar engines. Equation (2), page 47 can be used to find variables E-G in the following way:

To find variable E: use equation (2) (see page 47).

To find variable F: change idle to 30% thrust for all parts of equation (2).

58

To find variable G: change idle to 80% thrust for the CFM-56 engine and to 63% thrust

for the F110 engine.

Table 4-11

**C_xH_y, CO and CO_2 Concentrations for the KC-135/CFM-56 Engine
(JP-4 and JP-8)**

Pollutant	Fuel Type	Engine Modes		
		Idle	30%	80%
C_xH_y (ppmC)	JP-4	119.5	102.4*	51.2*
C_xH_y (ppmC)	JP-8	196.7	168.6*	84.3*
CO (ppm)	JP-4	640.3	173.3*	97.9*
CO (ppm)	JP-8	758.2	205.2*	116.0*
CO_2 (%)	JP-4	2.03	2.59*	4.87*
CO_2 (%)	JP-8	2.11	2.69*	5.06*

* - indicates estimated concentration

For example to find variable E for C_xH_y, substitute in the appropriate values results in:

$$E = \left(\frac{196.7}{119.5}\right) \bullet (7) = 11.52 \text{ ppmC } C_xH_y$$

Variables E-G for each pollutant are shown in Table 4-12.

Variable H and variable I will also be estimated the same as Method 1; the assumption

that % change in emissions at idle from JP-4 to JP-8 will be the same as intermediate and

afterburner will be used. Estimated concentrations for variables H and I are shown in

Table 4-12.

The values for Method 2 are for the most part identical to Method 1. This is probably

because both methods used the same assumptions for fuel and engine type differences. It

is interesting to note that the biggest difference is the estimated concentration for CO at

63% thrust. In Method 1, the measurement of JP-5 at 80% in the CFM-56 engine was not

detected. Consequently, the estimated concentration for the F110 engine operating on JP-

8 fuel was assumed to be the same as JP-4 fuel. Using Method 2, JP-5 data was not

59

needed. Thus, an estimated concentration could be developed. The value using Method 1 is still very close to Method 2.

Table 4-12

Estimated Concentrations for C_xH_y, CO, and CO_2 for F-16 C&D/F110 Engine (JP-8)- Method 2

Pollutant	Engine Modes				
	Idle	30%	63%	Intermediate	Afterburner
CxHy (ppmC)	11.52	9.88\	4.94	5.76	551.4
CO (ppm)	100.7	27.2	15.4	17.76	210.8
CO2 (%)	1.02	1.3	2.44	3.30	.43

Emission Factors

The calculation of the estimated emission factor for each HAP at each engine operating mode of the F-16 C&D/F110 engine operating on JP-8 fuel will be done using the results of the two methods discussed in the methodology. Since the two methods produced similar results, the calculation for Method 1 will only be shown. However, Tables 4-13 and 4-14 show the emission factors for all HAPs at each engine operating mode.

Method 1 The estimated concentrations for HAPs (Table 4-4) and C_xH_y, CO, and CO_2 (Table 4-10) for the F110 engine using JP-8 fuel was used to develop an emission factor for each HAP at each engine operating mode using the following equation:

$$EI(Z) = \left[\frac{[Z]}{[CO]+[CO_2]+C_xH_y - T}\right]\left[\frac{M_z \times 10^3}{M_c + \alpha M_H}\right]$$

To use this equation, the concentrations from Tables 4-14 and 4-10 must be converted to mole fraction concentrations. For convenience, the calculation of the estimated emission factor for one HAP (formaldehyde) at idle will be shown. The remaining emission factors will be calculated in the same manner. The developed emission factors using method 1 are shown in Table 4-13.

60

Formaldehyde. The variables in the equation can be found in the following manner:

1) [Z] = mole fraction concentration of HAP (formaldehyde)

From Table 4-4: formaldehyde = .436 ppmC

The first step is to convert ppmC to ppm:

ppm = (concentration in ppmC)/ (# of carbon atoms)

= (.436 ppmC)/ (1) = .436 ppm

The molecular formula for formaldehyde is HCHO so there is one carbon atom.

Next, convert ppm to mole fraction concentration by:

[formaldehyde] = ppm/10^6 = .436 ppm/10^6 = [4.36×10^{-7}]

2) [CO] = mole fraction concentration for carbon monoxide

From Table 4-10: CO = 100.7 ppm.

[CO] = 100.7 ppm/10^6 = [1×10^{-4}]

3) [C_xH_y] = mole fraction concentration for hydrocarbons

From Table 4-10: C_xH_y = 11.52 ppmC

Using assumption discussed in methodology that hydrocarbons are made up of methane (1 carbon atom): 11.52 ppmC = 11.52 ppm.

[C_xH_y] = 11.52 ppm/10^6 = [1.152×10^{-5}]

4) [CO_2] = mole fraction concentration of carbon dioxide

From Table 4-10: CO_2 = 1.02%

Since mole fraction concentration = %/100:

[CO_2] = 1.02%/100 = [.0102]

5) T = .00032 (mole fraction of CO_2 in dry inlet air)

6) M_z = molecular weight of formaldehyde = 30

7) M_C = molecular weight of carbon = 12.011

8) M_H = molecular weight of hydrogen = 1.008

9) α = 1.8 (assumption)

Substituting into the equation results in:

$$EI(HCHO) = \left(\frac{\left[4.36 \times 10^{-7}\right]}{\left[1 \times 10^{-4}\right] + \left[1.152 \times 10^{-5}\right] + \left[.0102\right] - .00032}\right) \bullet \left(\frac{30 \times 10^{3}}{12.011 + (1.8)(1.008)}\right)$$

EI (formaldehyde) = .0947 g formaldehyde/kg fuel or lb formaldehyde/1000 lb fuel

Estimated emission factors using method 2 are done in the same manner. They are shown in Table 4-14.

Table 4-13

Estimated HAP Emission Factors for F-16 C&D/F110 Engine (JP-8)- Method 1
(g/kg or lb/1000 lb)

HAP	Engine Modes				
	Idle	30%	63%	Intermediate	Afterburner
Formaldehyde	9.4E-2	3.9E-2	1.2E-2	8.6E-3	6.50
Benzene	1.4E-2	2.8E-3	1.5E-3	6.3E-4	2.17
Toluene	1.07E-1	2.5E-3	4.8E-4	2.4E-4	1.63
1,3 Butadiene	2.0E-3	4.6E-4	2.4E-4	6.0E-5	2.05
m&p-xylene	4.5E-3	1.6E-3	2.4E-4	5.9E-5	0.53
o-xylene	2.2E-3	5.3E-4	4.0E-5	2.9E-5	0.22
Ethylbenzene	2.2E-3	4.5E-4	8.0E-5	2.9E-5	0.27
Acetaldehyde	5.9E-2	3.0E-2	8.1E-3	4.1E-3	0.62
Acrolein	3.3E-3	1.1E-4	5.0E-4	2.1E-4	1.47

Table 4-14

Estimated HAP Emission Factors for F-16 C&D/F110 Engine (JP-8)- Method 2
(g/kg or lb/1000 lb)

HAP	Engine Modes				
	Idle	30%	63%	Intermediate	Afterburner
Formaldehyde	9.4E-2	4.0E-2	1.2E-2	8.6E-3	6.50
Benzene	1.4E-2	3.3E-2	1.3E-3	6.3E-4	2.17
Toluene	1.07E-1	2.9-3	4.8E-4	2.4E-4	1.63
1,3 Butadiene	2.0E-3	8.5E-4	4.5E-4	6.0E-5	2.05
m&p-xylene	4.5E-3	8.3E-4	1.2E-4	5.9E-5	0.53
o-xylene	2.2E-3	3.8E-4	8.0E-5	2.9E-5	0.22
Ethylbenzene	2.2E-3	4.5E-4	8.0E-5	2.9E-5	0.27
Acetaldehyde	5.9E-2	2.6E-4	7.3E-3	4.1E-3	0.62
Acrolein	3.3E-3	2.1E-4	7.9E-4	2.1E-4	1.47

Note: E refers to exponent; i.e., Formaldehyde at idle = 9.4 x 10^2

As can be seen by the two tables, the emission factors for both methods are very similar. The differences between the two methods occur at 30% and 63% thrust because the least data was available from past studies for these modes. Thus, it was necessary to use more estimation for these concentrations. In developing an emission inventory for 30% and 63%, emission factors from both methods could be used which would give a range of emissions for each HAP. However, given the small estimated emission factors for the F110 engine and the small differences between the two methods, this may not be necessary.

5. *Conclusions and Recommendations*

Conclusions for the two methods used to estimate the HAP concentrations for the F-16C&D aircraft/F110 engine using JP-8 fuel are presented and followed by an overall conclusion of the estimated emission factors and emission inventory for the F-16 C&D/F110 engine.

Conclusions

Selection of HAPs. The HAPs selected for this study represent the HAPs present in the greatest concentrations in the limited studies which have quantified exhaust constituents. The Spicer et al. study of 1984 on the CFM-56 and TF-39 engines, as well as the Spicer et al. study of 1990 on the F110 and F101 engines showed concentrations of all the selceted HAPs in the exhaust of all four engines. Only two additional HAPs (styrene, phenol) were also found in the engines. However, they were not selected for this study because of lower concentrations in the exhaust. None of the remaining 189 HAPs from Title III of the 1990 Clean Air Act have been shown to be present in the exhaust of any engines tested for constituents.

Use of Previous Studies to Propose F110 Engine/JP-8 Fuel HAP Concentrations. Because jet engine testing for HAPs has been extremely limited, it was first necessary to determine the availability of data from past HAP engine emission studies before a methodology could be determined for this study. Once the data was obtained, it was evident that data was lacking in some areas.

The methodology developed used two methods on the existing data to propose JP-8 HAP emissions for the F110 engine. Each method used different procedures to ultimately estimate F110 engine/JP-8 HAP concentrations. Both methods used to estimate the HAP concentrations at each engine operating condition produced very similar results. The reasons for the close similarity were mainly due to the same assumptions being employed

for both methods. These assumptions were used for fuel and engine type differences and their effect on exhaust concentrations for HAPs, total hydrocarbons, carbon monoxide and carbon dioxide.

Attempting to quantify the effect of engine type differences on HAP exhaust concentrations was extremely difficult because only two studies have taken place which quantified the HAPs in the exhaust. Although, there have been numerous studies to measure total hydrocarbons, carbon monoxide, and carbon dioxide, the key engine parameters which affect exhaust concentrations such as, fuel/air ratio, engine speed, engine operating temperature, and combustor operating pressure, are all changing from one engine to another. Thus, it is difficult to assess the effect each HAP has by itself. However, it does appear that the combustion efficiency of the engine does play a major part in the concentrations of C_xH_y and CO. The higher the combustion efficiency of the engine, tle lower the C_xH_y and CO emissions. The F110 engine, which is one of the newest engines, has a high combustion efficiency, and consequently, very low C_xH_y and CO emissions when compared to the CFM-56 engine.

It was difficult to assess the impact of engine type differences upon HAP exhaust emissions. Thus, the assumption was used in both methods that because the F110 and CFM56 engines are of similar design, their combustion processes should be similar.

Fuel type differences and their effect on exhaust concentrations seem to be heavily determined by the original make-up of the fuel. JP-5 and JP-8 fuels are made up of predominatly normal paraffins (carbon numbers C9 - C17), while JP-4 fuel contains mostly normal paraffins (carbon numbers C4 - C16) (Spicer et al., 1984:88). Since JP-5 and JP-8 are similar in their fuel make-up, their HAP exhaust concentrations are also approximately the same. Thus, the assumption was used that the HAP exhaust concentrations for the two fuels would be the same for all engine operating conditions. On the other hand, the make-up of JP-4 fuel is much different than JP-5 and JP-8 fuels. The HAP exhaust concentrations are also different. The second assumption was that the % change in

emissions from JP-5 to JP-4 would be the same at any engine operating condition. This was because the fuel was being burned in the same engine.

All the assumptions used in both methods resulted in similar exhaust concentrations. A second reason for the similar amounts was that the concentrations for CO, C_xH_y, and CO_2 were very low for the F110 engine. Thus, when the two methods were used, there was less variance in the estimated HAP concentrations for JP-8 fuel.

Emission Factor

The resultant estimated emission factors were very low for all nine selected HAPs when compared to previous emission factors for total hydrocarbons, carbon monoxide, and carbon dioxide. This was expected because of the low concentrations of HAPs, CO, C_xH_y, and CO_2 in the exhaust of the F110 engine. One would expect other engines, especially older engines, to have higher concentrations of each pollutant, and thus, higher emission factors.

As further testing is done on jet engines to quantify the exhaust constituents, more data will become available. There may be enough data available to use a different emission factor formula recommended by the SAE and ICAO which would give a more accurate HAP emission factor.

Emission Inventory

The emissions from each stage of the mission mode was low for each HAP primarily due to the low estimated emission factors for the F110 engine. However, the afterburner engine mode could be an area of potential concern. The longer the engine is in afterburner, the more HAP emissions will occur during a mission. Thus, the afterburner in an aircraft should be looked at as one area to try to find ways to reduce hydrocarbons and HAP emissions. However, the small time in modes for afterburner used in this study does not seem to indicate a potential problem.

A large part of the information in this study was derived from the the Seitchek 1985 study which gave typical mission modes and time in mode for a light aircraft. However, an F-16 mission is extremely hard to quantify because there is no "typical" F-16 mission. Each mission could have different time in modes or different engine operating cycles depending on the purpose of the mission. Thus, it is important to take this into account when compiling a HAP emission inventory. Also, once a HAP emission inventory is compiled, the total emissions for each HAP should be reviewed against the risk assessment for that HAP to determine if an air quality problem may exist.

The importance of this thesis is that it proposes emission factors for the F110 engine using JP-8 fuel. The fact that the emission factors were derived in part by using the data from HAP emissions for the same engine using JP-4 fuel, makes these emission factors more credible. The only other study which proposed emission factors for HAPs at all engine operating conditions was the AESO 1991 study which propsed the emission factors for JP-5 fuel. This study used the Spicer 1984 study on the CFM-56 and TF-39 engines and assumed that the percentage of HAPs found in these engines would be found in all engines. They used this assumption in developing the emission factors. However, data from the F110 engine reveals that HAPs may be available in much lower concentrations in newer, more efficient engines.

The estimated emission factors found in this study can be used to compile HAP emission inventories as shown in Appendix A. Although federal regulations for HAP area sources have not yet been defined, it is interesting to note that if the current regulations for major sources were applied to the nine HAPs in this study that five of the HAPs (formaldehyde, benzene, toluene, 1,3-butadiene, and acrolein) would be classified as major sources because they all exceed the 10 tons per year requirement. Although the HAP emissions inventory was based on only one type of F-16 C&D mission, it shows the importance of verifying estimates of HAP emissions by compiling an emissions inventory. Based on the upcoming regulations regarding HAP emissions inventories, the Air Force

67

should seriously consider assessment of the flying operations at each base to assume compliance with Title III requirements. A more accurate emission factor could be found by performing actual measurements of the exhaust of an F-16/F110 engine. However, until the testing takes place, the estimated emission factors from this study should be used.

Further Research Recommendations

The purpose of this research was to expand the knowledge base of emissions from DoD aircraft. However, this thesis does not by any means conclude research in this area. More research would improve the knowledge in this area and possibly provide solutions. Further research efforts may be done in the following areas:

(1) Develop emission factors for other Air Force aircraft using JP-8 fuel. The Air Force is in the process of updating the AQUIS database which provides speciated JP-8 data for all Air Force aircraft and their respective engines. More research can assess the validity of the data which could be used to develop emission factors for other Air Force engines.

(2) Perform a more in-depth analysis of emission factors and determine if a more accurate emission factor exists for aircraft. A possible way to perform this research would be to research the methods used by commercial industry or other DoD agencies to report their aircraft emissions and compare the method against the Air Force method.

(3) Perform a study on the HAPs found in aircraft exhaust and determine their atmospheric life or chemical fate. This will provide better information on which of the 189 HAPs should be a concern with regards to aircraft. The results of such research could also aid in performing a risk assessment for each HAP.

(4) Determine methods to quantify HAP emissions from other Air Force operations. The requirement for HAP emission inventories does not apply to only aircraft but will be necessary for any Air Force operation which emits HAPs such as wastewater plants, paint shops, solvent operations, etc. Methods to quantify the HAPs emitted from

these operations could be researched, and consequently, emission factors could be proposed for these operations. This would give the Air Force a good start in compiling HAP emission inventories for all their operations and would allow us to immediately meet the HAP emission inventory requirement of the 1990 CAA once the EPA announces when such inventories will be required.

Appendix A: Emission Inventory for F-16C&D Airfield Operation

To compile an emission inventory, the total emissions will need to be found for each stage of a typical F-16 mission. Table A-1 lists the eleven mission modes along with the time spent in each mode and the engine operating condition for each mission mode. The emissions from all eleven stages will be summed to give total emissions from one aircraft mission.

Table A-1

Mission Mode/Engine Mode/Time In Mode For Typical Light Aircraft

Mission Mode	Engine Thrust Setting	Time In Mode (minutes)
Start-Up	Idle	6.3
Outbound Taxi	Idle	5.5
Engine Check	Military	1.1
Runway Roll	Afterburner	0.4
Climbout 1	Afterburner	0.4
Climbout 2	Military	0.3
Approach 1	Approach	1.9
Approach 2	Approach	0.7
Landing	Idle	1.1
Inbound Taxi	Idle	5.5
Idle at Shutdown	Idle	0.8

(Adapted from Seitchek, 1985: 24, 26)

As mentioned in Chapter 3, the following formula will be used to calculate emissions for each mission mode:

W (mission mode) = N• F(engine mode)• t(mission mode)• e (engine mode)

For the F-16 C&D/F110 engine:

N = # of engines = 1

F = fuel flow (kg/s): see Table A-2

t = time in mode: see Table A-1.

e = estimated emission factors from Tables 4-13 and 4-14.

Table A-2

Fuel Flows for Differing Engine Modes

Engine Mode	Fuel Flow (kg/s)
Idle	.133
30%	.312
63%	.697
Intermediate	1.26
Afterburner	5.797

(Spicer et al., 1990 and Fagin, 1988)

The fuel flows in Table A-2 were the fuel flows used to test the F110 engine in Spicer 's 1990 study with the exception of afterburner. The fuel flow for afterburner was not available. Instead, the fuel flow for afterburner listed in the table was taken from Fagin's 1988 study. The value listed is for the F100 engine which appears in the older model F-16s but still provides a relatively close value for the F110 engine.

Table A-1 shows the eleven mission modes, the engine operating condition and the tim in mode for each portion of the mission. For example, during the start-up portion of the mission, the engine operates at idle and start-up takes 6.3 minutes.

Table A-1 was taken from a 1985 study by Seitchek. This study refers to the F-16 engine modes as idle, approach, intermediate, military and afterburner. From reviewing the engine emissions data provided in this study, these engine modes appear to be equivalent to those tested in the Spicer et al. 1990 study on the F110 engine. Table A-3 shows the comparison between engine operating modes of the two studies.

Table A-3

Comparison of Engine Operating Modes for the F-16 From Two Studies

Seitchek 1985 Study	Spicer et al. 1990 Study
Idle	Idle
Approach	30% thrust
Intermediate	63% thrust
Military	Intermediate
Afterburner	Afterburner

From review of the Seitchek and Spicer et al. studies, it is assumed that the listed engine operating modes for each study are equivalent in the manner shown in Table A-3. The military operating mode referenced in the Seitchek study refers to the engine operating at full capacity (not including afterburner). For this reason, the intermediate engine mode from the Spicer study was said to be equivalent to military because intermediate is 105% power. The equivalent F110 engine modes will be used in compiling the HAP emissions inventory.

As mentioned in Chapter 3, emissions will be found for only the landing and takeoff (LTO) aircraft operations. This will be accomplished by finding the emissions for each mission mode found in Table A-1 and then adding them.

The final assumption to make is an estimate of the number of LTO operations on an airfield for a given year. Normally, base operations can provide this information to base environmental personnel. For purposes of this study, 30,000 LTOs will be assumed for the given year.

Compiling The Inventory

Using the aircraft modes from Table A-1, the emissions for each portion of the mission can be calculated. The estimated emission factors used in the equation will be taken from method 1. The following example will show a emission inventory for formaldehyde.

1) Start -Up

$W(start\text{-}up) = N \bullet F(idle) \bullet t(start\text{-}up) \bullet e(idle)$

where:

N = 1

F(idle) = .133 kg/s

t(start-up) = 6.3 m or 378 s

e(idle) = 9.4E-2 g formaldehyde/kg fuel (Table 4-13)

Substituting the values into the equation results in:

W(start-up) = 4.73 g of formaldehyde

2) Outbound Taxi

W(outbound taxi) = N • F(idle) • t(outbound taxi) • e(idle)

where:

N = 1

F(idle) = .133 kg/s

t(outbound taxi) = 5.5m or 330s

e(idle) = 9.4E-2 g formaldehyde/kg fuel

W(outbound taxi) = 4.13 g of formaldehyde

3) Engine Check

W(engine check) = N • F(intermediate) • t(engine check) • e(intermediate)

where:

N = 1

F(intermediate) = 1.26 kg/s

t(engine check) = 1.1 m or 66s

e(intermediate) = 8.6E-3 g fromaldehyde/kg fuel

W(engine check) = .72 g of formaldehyde

4) Runway Roll

W(runway roll) = N • F(afterburner) • t(runway roll) • e(afterburner)

where:

N = 1

F(afterburner) = 5.797 kg/s

t(runway roll) = .4 m or 24 s

e(afterburner) = 6.5

W(runway roll) = 904.3 g of formaldehyde

5) Climbout 1

The fuel flow, time in mode and estimated emission factor for climbout 1 is the same as runway roll. Thus:

W(climbout 1) = 904.3 g of formaldehyde

6) Climbout 2

W(climbout 2) = N • F(intermediate) • t(climbout 2) • e(intermediate)

where:

N = 1

F(intermediate) = 1.26 kg/s

t(climbout 2) = .3 m or 20 s

e(intermediate) = 8.6E-3 g fromaldehyde/kg fuel

W(climbout 2) = .22 g of formaldehyde

7) Approach 1

W(approach 1) =   N • F(30% thrust) • t(approach 1) • e(30% thrust)

where:

N = 1

F(30% thrust) = .312 kg/s

t(approach 1) = 1.9 m or 114s

e(30% thrust) = 4E-2 g formaldehyde/kg fuel

W(approach 1) = 1.42 g of formaldehyde

8) Approach 2

W(approach 2) = N • F(30% thrust) • t(approach 2) • e(30% thrust)

where:

N = 1

F(30% thrust) = .312 kg/s

t(approach 2) = .7 m or 42 s

e(30% thrust) = 4E-2 g formaldehyde/kg fuel

W(approach 1) = 0.52 g of formaldehyde

9) Landing

W(landing) = $N \cdot F(idle) \cdot t(landing) \cdot e(idle)$

where:

$N = 1$

F(idle) = .133 kg/s

t(outbound taxi) = 1.1m or 66s

e(idle) = 9.4E-2 g formaldehyde/kg fuel

W(landing) = 0.83 g of formaldehyde

10) Inbound taxi

W(inbound taxi) = $N \cdot F(idle) \cdot t(inbound \ taxi) \cdot e(idle)$

where:

$N = 1$

F(idle) = .133 kg/s

t(inbound taxi) = 5.5m or 330 s

e(idle) = 9.4E-2 g formaldehyde/kg fuel

W(inbound taxi) = 4.13 g of formaldehyde

11) Idle at shutdown

W(idle at shutdown) = $N \cdot F(idle) \cdot t(idle \ at \ shutdown) \cdot e(idle)$

where:

$N = 1$

F(idle) = .133 kg/s

t(inbound taxi) = 0.8m or 48 s

e(idle) = 9.4E-2 g formaldehyde/kg fuel

W(idle at shutdown) = 0.6 g of formaldehyde

Next, add up the emissions from Stages 1-11 results in:

W(formaldehyde) = 1,825.9 g of formaldehyde per LTO operation

Assuming 30,000 LTOs per year:

W(formaldehyde) = 1,825.9 g of formaldehyde • 30,000

= 54,777 kg of formaldehyde per year

The same process can be used for the remaining eight HAPs. The total emissions for each LTO mission is attached.

Table A-4

Total Emissions of Benzene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	0.014	0.703836
Outbound Taxi	1	0.133	330	0.014	0.61446
Engine Check	1	1.26	66	6.30E-04	0.052391
Runway Roll	1	5.797	24	2.17	301.9078
Climbout 1	1	5.797	24	2.17	301.9078
Climbout 2	1	1.26	18	6.30E-04	0.014288
Approach 1	1	0.312	114	2.80E-03	0.09959
Approach 2	1	0.312	42	2.80E-03	0.036691
Landing	1	0.133	66	0.014	0.122892
Inbound Taxi	1	0.133	330	0.014	0.61446
Idle at Shutdown	1	0.133	48	0.014	0.089376
				Total W per LTO	606.1635
				Total W per year	18184905

Table A-5

Total Emissions of Toluene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	0.107	5.379318
Outbound Taxi	1	0.133	330	0.107	4.69623
Engine Check	1	1.26	66	2.40E-04	0.019958
Runway Roll	1	5.797	24	1.63	226.7786
Climbout 1	1	5.797	24	1.63	226.7786
Climbout 2	1	1.26	18	2.40E-04	0.005443
Approach 1	1	0.312	114	2.50E-03	0.08892
Approach 2	1	0.312	42	2.50E-03	0.03276
Landing	1	0.133	66	0.107	0.939246
Inbound Taxi	1	0.133	330	0.107	4.69623
Idle at Shutdown	1	0.133	48	0.107	0.683088
				Total W per LTO	470.0985
				Total W per year	14102954

Table A-6

Total Emissions of 1,3-Butadiene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	0.002	0.100548
Outbound Taxi	1	0.133	330	0.002	0.08778
Engine Check	1	1.26	66	6.00E-05	0.00499
Runway Roll	1	5.797	24	2.05	285.2124
Climbout 1	1	5.797	24	2.05	285.2124
Climbout 2	1	1.26	18	6.00E-05	0.001361
Approach 1	1	0.312	114	4.60E-04	0.016361
Approach 2	1	0.312	42	4.60E-04	0.006028
Landing	1	0.133	66	0.002	0.017556
Inbound Taxi	1	0.133	330	0.002	0.08778
Idle at Shutdown	1	0.133	48	0.002	0.012768
				Total W per LTO	570.76
				Total W per year	17122799

Table A-7

Total Emissions of m&p-xylene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	4.50E-03	0.226233
Outbound Taxi	1	0.133	330	4.50E-03	0.197505
Engine Check	1	1.26	66	5.90E-05	0.004906
Runway Roll	1	5.797	24	0.53	73.73784
Climbout 1	1	5.797	24	0.53	73.73784
Climbout 2	1	1.26	18	5.90E-05	0.001338
Approach 1	1	0.312	114	1.60E-03	0.056909
Approach 2	1	0.312	42	1.60E-03	0.020966
Landing	1	0.133	66	4.50E-03	0.039501
Inbound Taxi	1	0.133	330	4.50E-03	0.197505
Idle at Shutdown	1	0.133	48	4.50E-03	0.028728
				Total W per LTO	148.2493
				Total W per year	4447478

Table A-8

Total Emissions of o-xylene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	2.20E-03	0.110603
Outbound Taxi	1	0.133	330	2.20E-03	0.096558
Engine Check	1	1.26	66	2.90E-05	0.002412
Runway Roll	1	5.797	24	0.22	30.60816
Climbout 1	1	5.797	24	0.22	30.60816
Climbout 2	1	1.26	18	2.90E-05	0.000658
Approach 1	1	0.312	114	5.30E-04	0.018851
Approach 2	1	0.312	42	5.30E-04	0.006945
Landing	1	0.133	66	2.20E-03	0.019312
Inbound Taxi	1	0.133	330	2.20E-03	0.096558
Idle at Shutdown	1	0.133	48	2.20E-03	0.014045
				Total W per LTO	61.58226
				Total W per year	1847468

Table A-9

Total Emissions of Ethylbenzene Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	2.20E-03	0.110603
Outbound Taxi	1	0.133	330	2.20E-03	0.096558
Engine Check	1	1.26	66	2.90E-05	0.002412
Runway Roll	1	5.797	24	0.27	37.56456
Climbout 1	1	5.797	24	0.27	37.56456
Climbout 2	1	1.26	18	2.90E-05	0.000658
Approach 1	1	0.312	114	4.50E-04	0.016006
Approach 2	1	0.312	42	4.50E-04	0.005897
Landing	1	0.133	66	2.20E-03	0.019312
Inbound Taxi	1	0.133	330	2.20E-03	0.096558
Idle at Shutdown	1	0.133	48	2.20E-03	0.014045
				Total W per LTO	75.49117
				Total W per year	2264735

Table A-10

Total Emissions of Acetaldehyde Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	5.90E-02	2.966166
Outbound Taxi	1	0.133	330	5.90E-02	2.58951
Engine Check	1	1.26	66	4.10E-03	0.340956
Runway Roll	1	5.797	24	0.62	86.25936
Climbout 1	1	5.797	24	0.62	86.25936
Climbout 2	1	1.26	18	4.10E-03	0.092988
Approach 1	1	0.312	114	3.00E-02	1.06704
Approach 2	1	0.312	42	3.00E-02	0.39312
Landing	1	0.133	66	5.90E-02	0.517902
Inbound Taxi	1	0.133	330	5.90E-02	2.58951
Idle at Shutdown	1	0.133	48	5.90E-02	0.376656
				Total W per LTO	183.4526
				Total W per year	5503577

Table A-11

Total Emissions of Acrolein Per Year (grams)

	N	F(kg/s)	t(sec)	e(g/kg fuel)	W(g)
Start-Up	1	0.133	378	3.30E-03	0.165904
Outbound Taxi	1	0.133	330	3.30E-03	0.144837
Engine Check	1	1.26	66	2.10E-04	0.017464
Runway Roll	1	5.797	24	1.47	204.5182
Climbout 1	1	5.797	24	1.47	204.5182
Climbout 2	1	1.26	18	2.10E-04	0.004763
Approach 1	1	0.312	114	1.10E-04	0.003912
Approach 2	1	0.312	42	1.10E-04	0.001441
Landing	1	0.133	66	3.30E-03	0.028967
Inbound Taxi	1	0.133	330	3.30E-03	0.144837
Idle at Shutdown	1	0.133	48	3.30E-03	0.021067
				Total W per LTO	409.5695
				Total W per year	12287085

Table A-12 lists the total emissions for each HAP in tons per year. This table was compiled by converting the emissions in grams for each HAP (Tables A-4 to A-11) to emissions in tons per year

Table A-12

Total Emissions for HAPs (Tons per year)

HAP	Total Emissions (tons per year)
Formaldehyde	60.4
Benzene	20.0
Toluene	15.5
1,3-Butadiene	18.9
m&p-xylene	4.9
o-xylene	2.0
Ethylbenzene	2.5
Acetaldehyde	6.1
Acrolein	13.5

Title III of the 1990 CAA lists a major source as any stationary source which emits 10 tons per yewar of any single HAP or 25 tons per year of a combination of HAPs. Aircraft are categorized as area sources. The only current requirement for area sources is that the EPA must take steps to assure that 90% of the emissions of the 30 most serious area source pollutants are regulated within 10 years (Quarles et al., 1990:34). Assuming the same classifications of area sources as for major sources, only four HAPs(m&p-xylene, o-xylene, ethylbenzene, and acetaldehyde) would be under 10 tons per year. Also, the requirement of 25 tons per year for a combination of HAPs would be greatly exceeded.

Using the emissions calculated previously, it can be determined the number of missions which will be allowable before exceeding the 10 tons per year requirement for a single HAP or 25 tons per year for a combination of HAPs. Since formaldehyde, has the highest amount of emissions, the number of missions will be calculated for this HAP using the 10 tons per year requirement. Using the equation:

W(formaldehyde) = 1,825.9 g of formaldehyde • # of missions

where:

W = 10 tons per year or 9,071,847.4 grams

This results in 4,968 missions. Table A-13 shows the emissionsm for all nine HAPs (in tons per Year) for 4,968 missions.

Table A-13

HAP Emissions for 4,968 Missions (tons per year)

HAP	Total Emissions (tons per year)
Formaldehyde	9.99
Benzene	3.32
Toluene	2.57
1,3-Butadiene	3.13
m&p-xylene	.81
o-xylene	.34
Ethylbenzene	.41
Acetaldehyde	1.00
Acrolein	2.24
Total	23.81

Using 4,968 missions, the individual HAPs are less than 10 tons per year and the total is less than 25 tons per year. Thus, 4,968 would be the maximum number of LTOs allowed per year.

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Vita

Captain Donald J. Van Schaack was born on 29 Jul 1959 in Brooklyn, New York. He graduated from Tottenville High School in Staten Island, New York in 1977. He attended Baylor University where he earned a Bachelor of Science degree in Engineering Science. After graduation, he earned a commission in the United States Air Force through USAF Officer Training School in August, 1983. Captain Van Schaack initially entered an Air Force Institute of Technology Civilian Institute Program at Ohio University in Athens, Ohio. He received a Bachelor of Science degree in Electrical Engineering in November, 1985. Upon graduation, Captain Van Schaack was assigned to the 44th Civil Engineering Squadron, Ellsworth AFB, South Dakota as an electrical design engineer and later as Chief of the Special Design Team and Chief of Heavy Rpair. In September 1989, Captain Van Schaack was reassigned to the 16 AF War Support Center as the Chief of Engineering for the USAF Southern Region Collocated Operating Bases (COBs). In September 1991, Captain Van Schaack was reassigned to the 7th Civil Engineering Squadron as an environmental engineer. He entered the Engineering and Environmental Management Program, School of Engineering, AFIT in May 1993. Upon graduation in September 1994, he will be assigned to Aeronautical Systems Command (ASC) Environmental Management Office at Wright-Patterson AFB, Ohio.

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DEVELOPING AN EMISSION FACTOR FOR HAZARDOUS AIR POLLUTANTS FOR AN F-16 USING JP-8 FUEL

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13. ABSTRACT (Maximum 200 words)

The 1990 Clean Air Act amendments drastically changed the legislation of hazardous air pollutants (HAPs) or air toxics. Title III of the act which specifically addresses HAPs now lists 189 substances which may require regulation as air toxics. Consequently, the reporting of HAP emissions from all Air Force operations will be required in the future. However, the Department of Defense (DoD) does not have methods available to report this information.

This thesis develops emission factors for selected HAPs from an F-16 C&D aircraft/F110 engine operating on JP-8 fuel. The methodology included: (1) determining which HAPs should be selected, (2) using past aircraft emission studies to estimate HAP concentrations for the F110 engine using JP-8 fuel, (3) selecting an emission factor formula to calculate emission factors for each HAP, (4) testing the developed emission factors on an airfield operation.

The estimated emission factors for each HAP for the F110 engine are low for all engine modes mainly because the F110 is a newer engine with high combustion efficiency. The resultant emission inventory shows that many HAPs would be classified as major sources under current Title III legislation. Thus, it is important to assess airfield operations to ensure they remain in compliance with the upcoming Title III legislation.

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